

Specification of ISS Plasma Environment Variability

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Abstract

Quantifying the spacecraft charging risks and corresponding hazards for the International Space Station (ISS) requires a plasma environment specification describing the natural variability of ionospheric temperature and density. Empirical ionospheric specification and forecast models such as the International Reference Ionosphere (IRI) model typically only provide estimates of the long term (seasonal) mean electron temperature and density values for the low Earth orbit environment. Knowledge of the electron temperature and density variability as well as the likelihood of extreme deviations from the mean values are required to estimate both the magnitude and frequency of occurrence of potentially hazardous spacecraft charging environments for a given ISS construction stage and flight configuration.

This paper describes the statistical analysis of historical ionospheric low Earth orbit plasma measurements used to estimate the variability of density (N_e) and temperature (T_e) in the ISS flight environment. The statistical variability analysis of N_e and T_e enables calculation of the expected frequency of occurrence of any particular values of N_e and T_e , especially those that correspond to possibly hazardous spacecraft charging environments. The database used in the original analysis included measurements from the AE-C, AE-D, and DE-2 satellites. Recent work on the database has added additional satellites to the database and ground based incoherent scatter radar observations as well. Deviations of the data values from the International Reference Ionosphere estimated N_e , T_e parameters for each data point provide a statistical basis for modeling the deviations of the plasma environment from the IRI model output. This technique, while developed specifically for the Space Station, can also be generalized to

provide ionospheric plasma environment risk specification models for low Earth orbit over an altitude range of 200 km through approximately 1000 km.

Ionospheric Properties and Variability

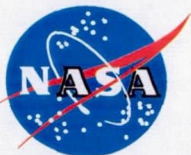
ISS Plasma TIM

Huntsville, AL 28-30 May 2003

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Sverdrup Technology, Inc.

Marshall Space Flight Center Group



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Overview

- **Brief review of work to date**
- **Current work**
 - **New data**
 - **Documentation**
 - **Forward word (schedule)**



Brief review of work to date



Variability Study

- ISS Program requires estimate of Te, Ne variability:
 - range of possible values at ISS altitudes
 - statistical variations in parameters
 - values for sunrise (eclipse exit) at high latitude particularly important
- Ionosphere models (e.g., IRI-90, IRI-95) don't contain information on variability at short time scales
 - IRI 2001 does contain modules to include geomagnetic storms
- Models are too “smooth”
 - data is required to obtain variability in environment about mean values
- Analysis of historical spacecraft data can provide estimate of variability ($n\sigma$ or other statistical figure of merit) in ionospheric parameters



Data

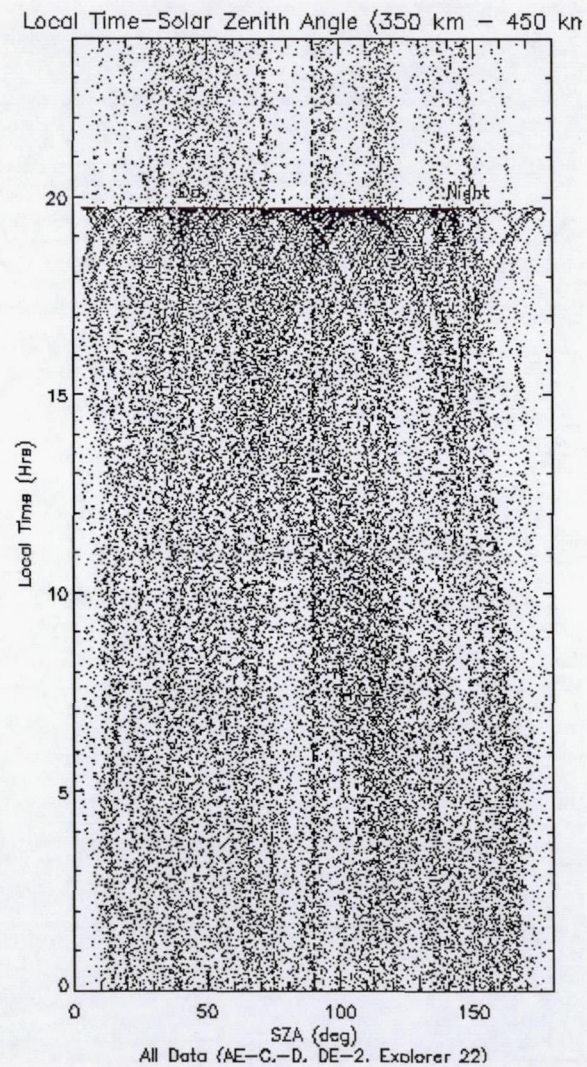
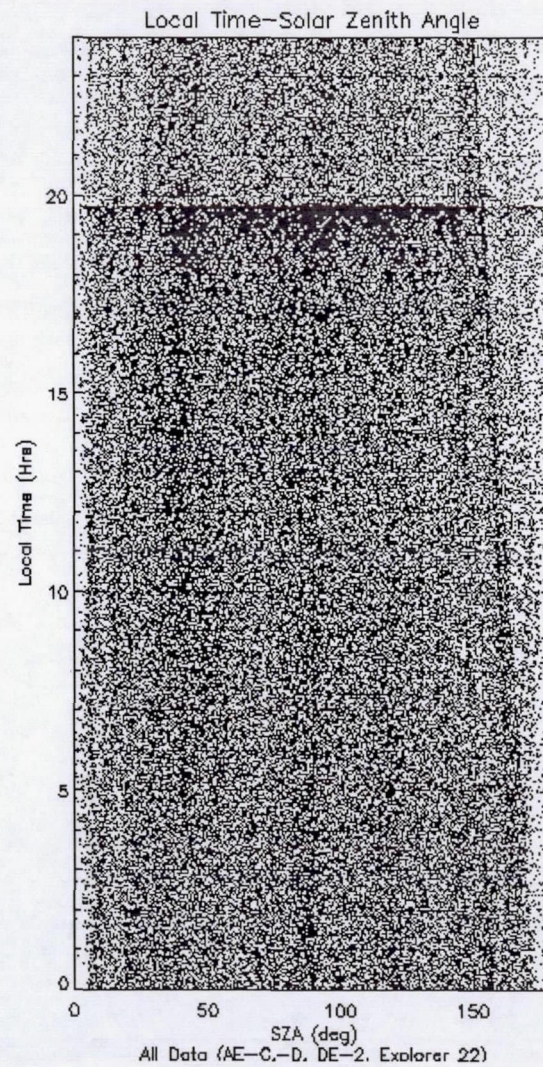
Spacecraft	Data Used in Study
• AE-C - Circular, 68.1 deg inc - Elliptical 150 km x 4300 km x 68.1 deg inc - 1973-12-16-00-00 - 1978-12-11-59-59	[1973-12-16 to 1978-12-11] 608,139 records*
• AE-D - Circular, 90.1 deg inc - Elliptical, 154 km x 3816 km x 90.1 deg inc - 1975-10-06-00-00 - 1976-01-29-59-59	[1975-10-06 to 1976-01-29] 100,395 records*
• AE-E - Circular, 19.7 deg inc - Elliptical, 156 km x 2983 km x 90.1 deg inc - 1975-12-01-00-00 - 1981-06-06	[1975-12-01 to 1981-05-24] 464,690 records*
• DE 2 - Elliptical, 300 km x 1000 km x 89.99 deg - 1981-08-06-00-00 - 1983-02-15-59-59	[1981-08-06 to 1983-02-15] 693,112 records*
• Explorer 22 - 889 km x 1081 km x 79.7 deg - 1964-10-10 to 1967-08-26	[1964-10-10 to 1967-08-26] 37,476 records*
• Explorer 31 - 500 km x 3000 km x 79.8 deg - 1965-10-29 to 1968-08-20	[1965-10-29 to 1968-08-20] 55,870 records* Total 1,959,651 records*

*Valid records in original data sets obtained from National Space Science Data Center. Not all records contain both Ne and Te values.

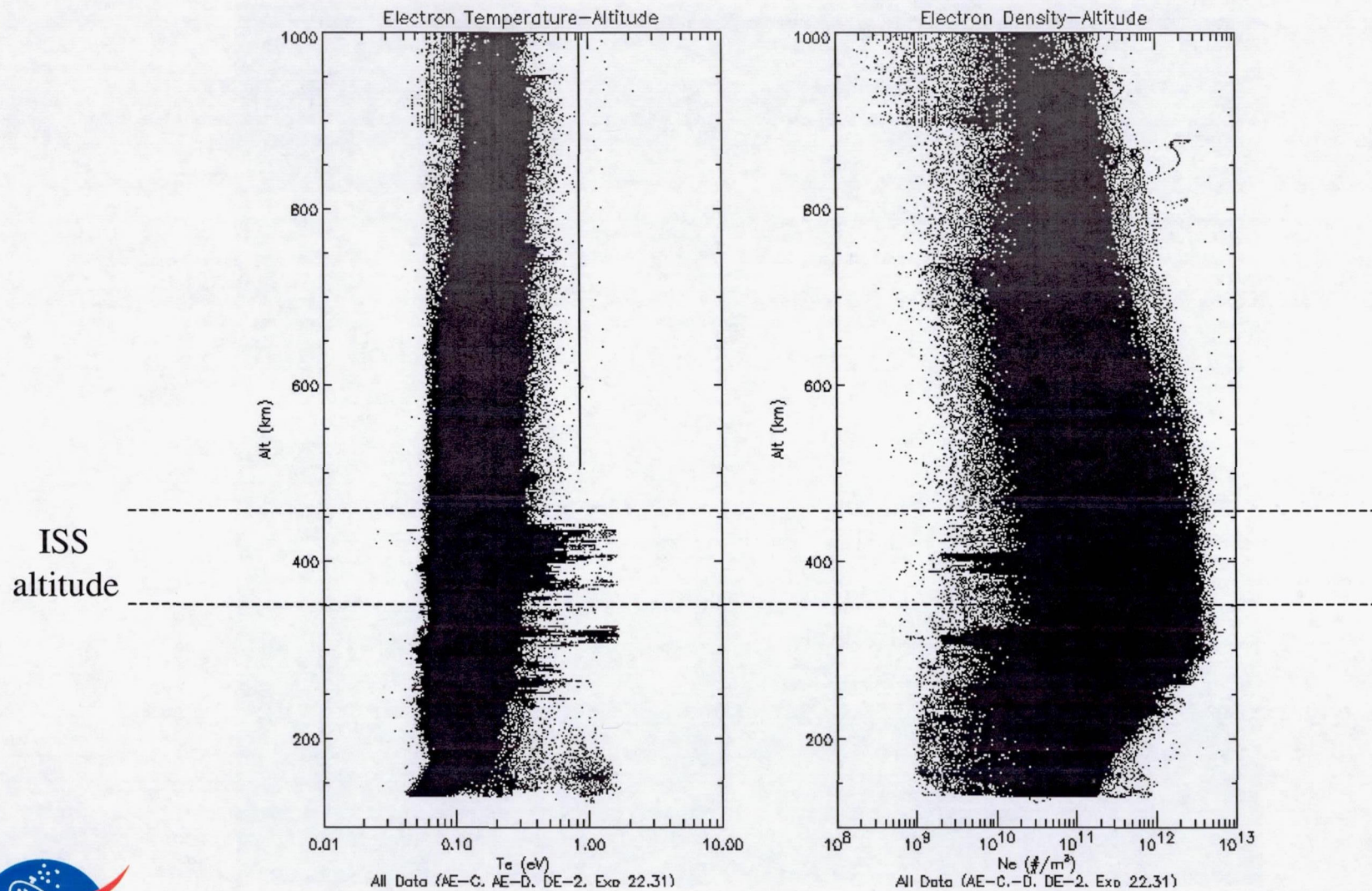


Local Time-Solar Zenith Angle

Current database



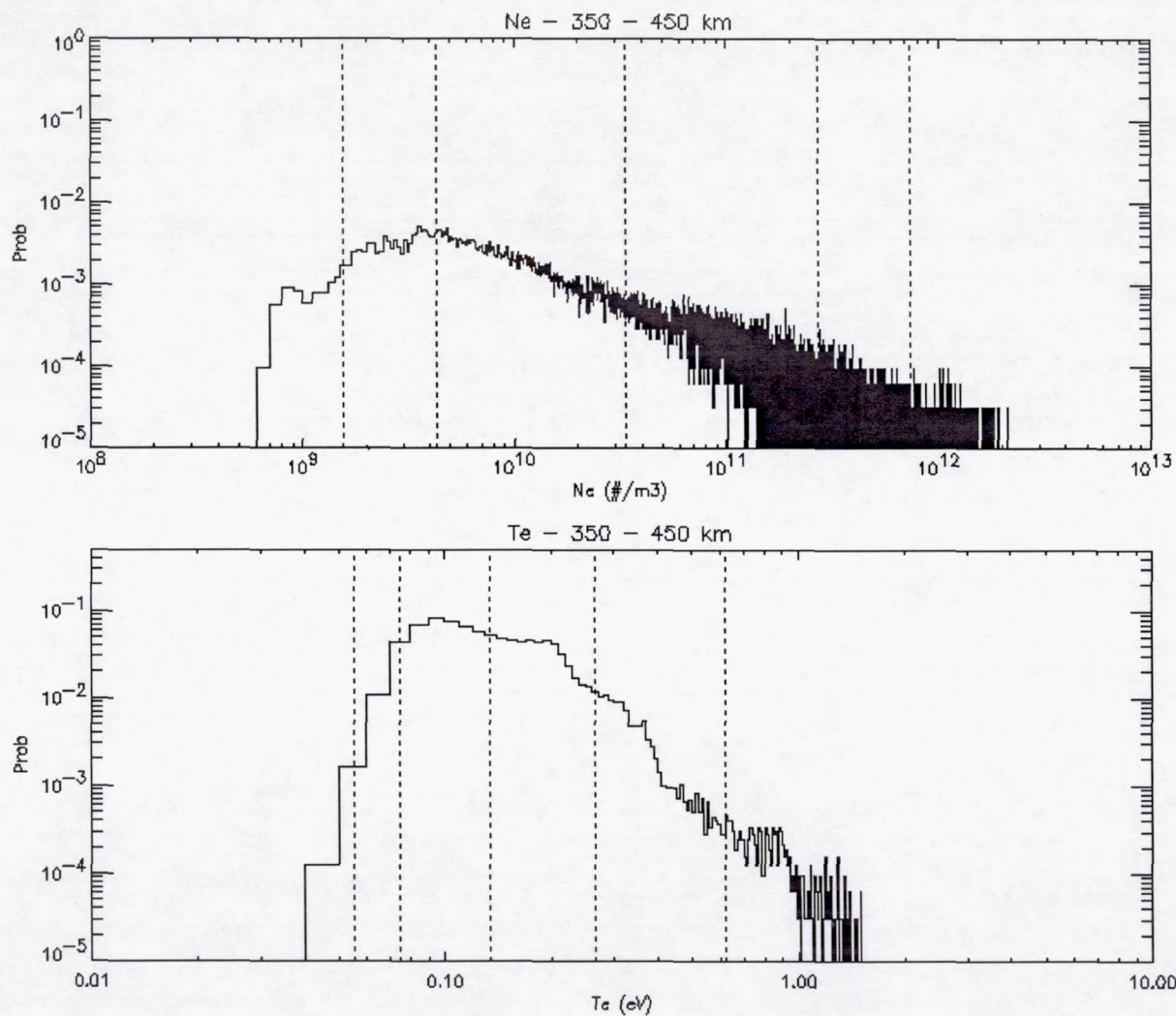
Te, Ne vs Altitude



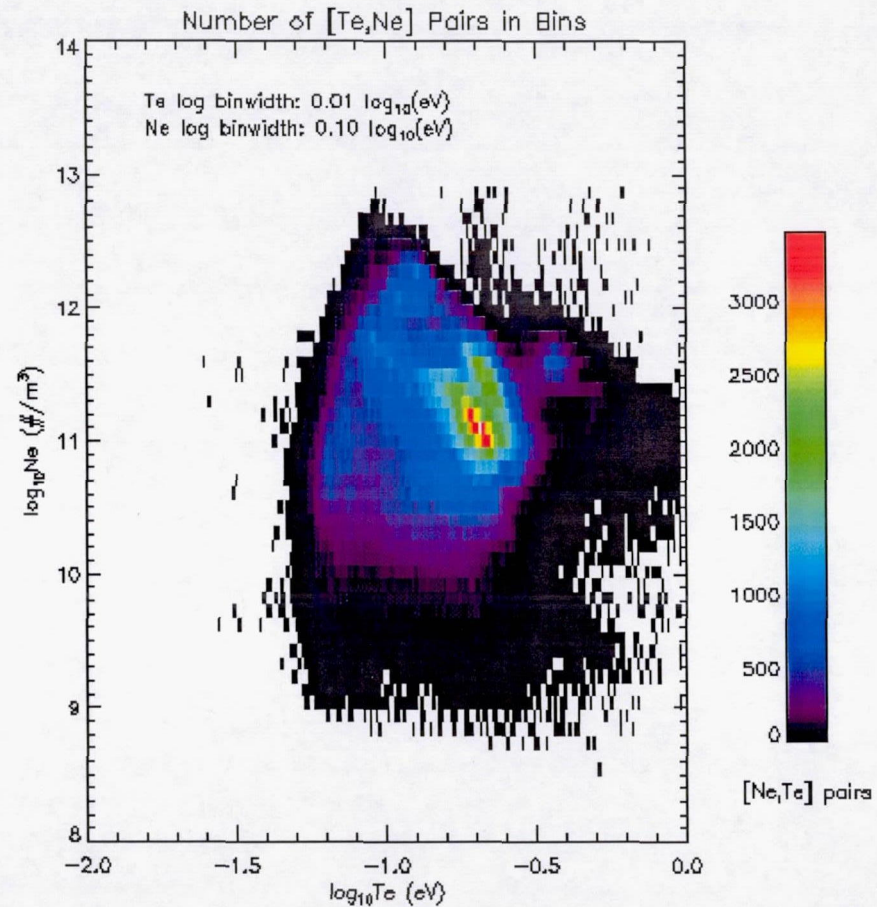
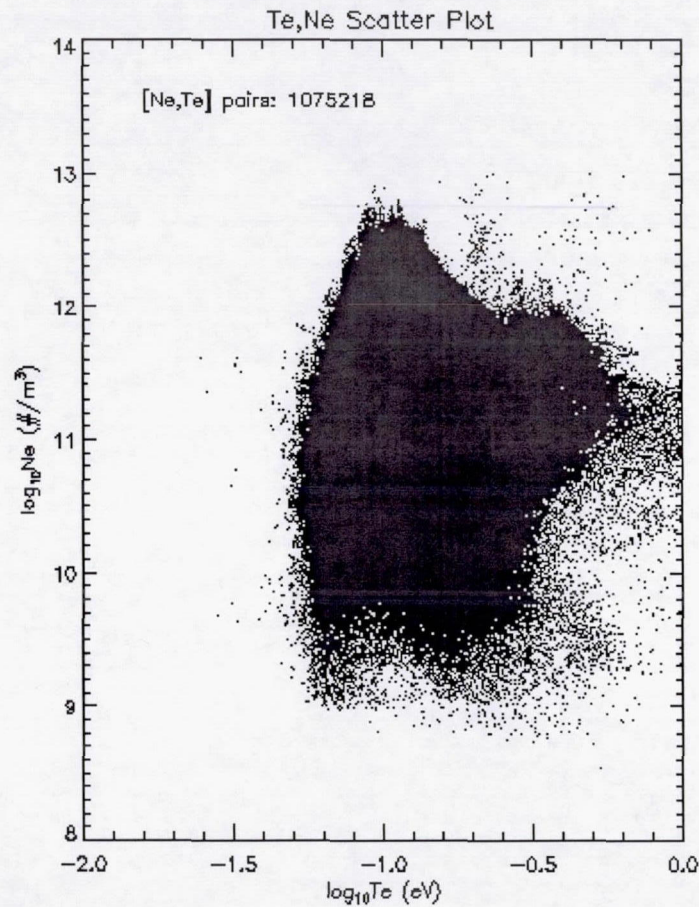
Statistics 350-450 km

Vertical dotted
lines mark
percentiles:

1%
10%
50%
90%
99%



Ne, Te Scatter Plots



$\sim 1.07 \times 10^6$ values

$200 \text{ km} < z < 1000 \text{ km}$

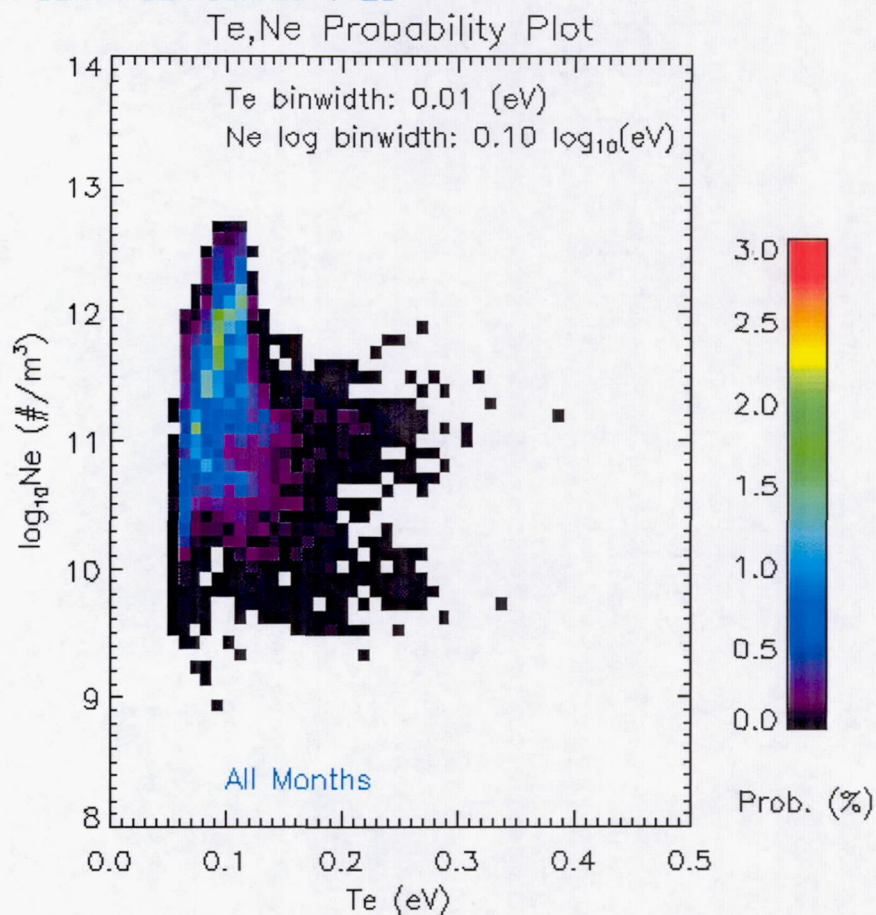
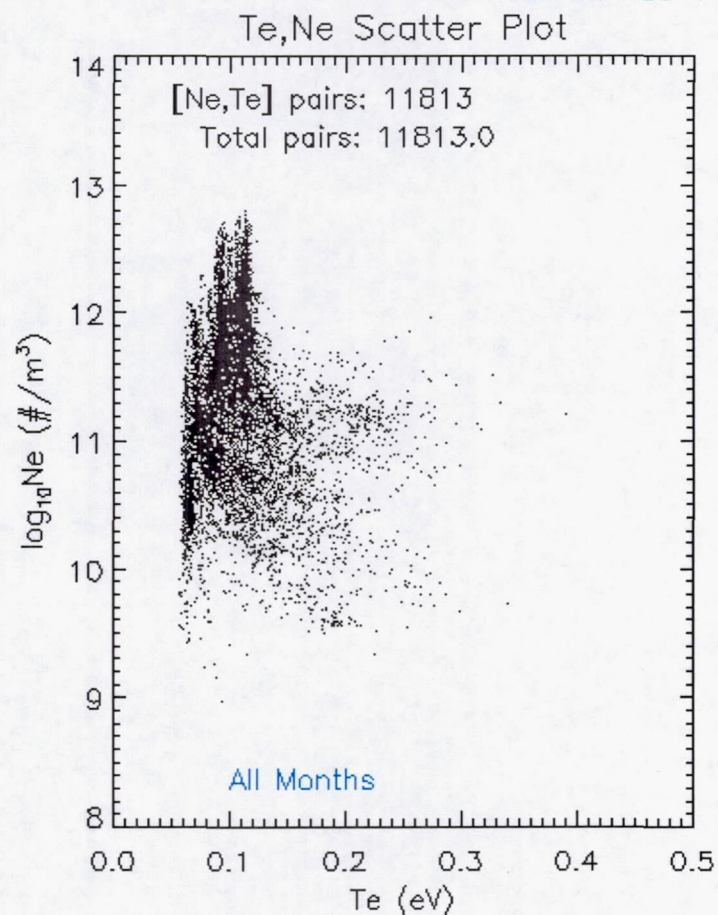
$-90.0^\circ \leq \text{latitude} \leq +90.0^\circ$

$0^\circ < \text{SZA} < 180^\circ$



ISS Filtered Ne, Te Scatter Plots

-51.6 < lat < 51.6, 350 km < z < 450 km, no AE-E
 SZA sunrise + 0 < SZA < SZA sunrise + 20



~1.18x10⁴ values

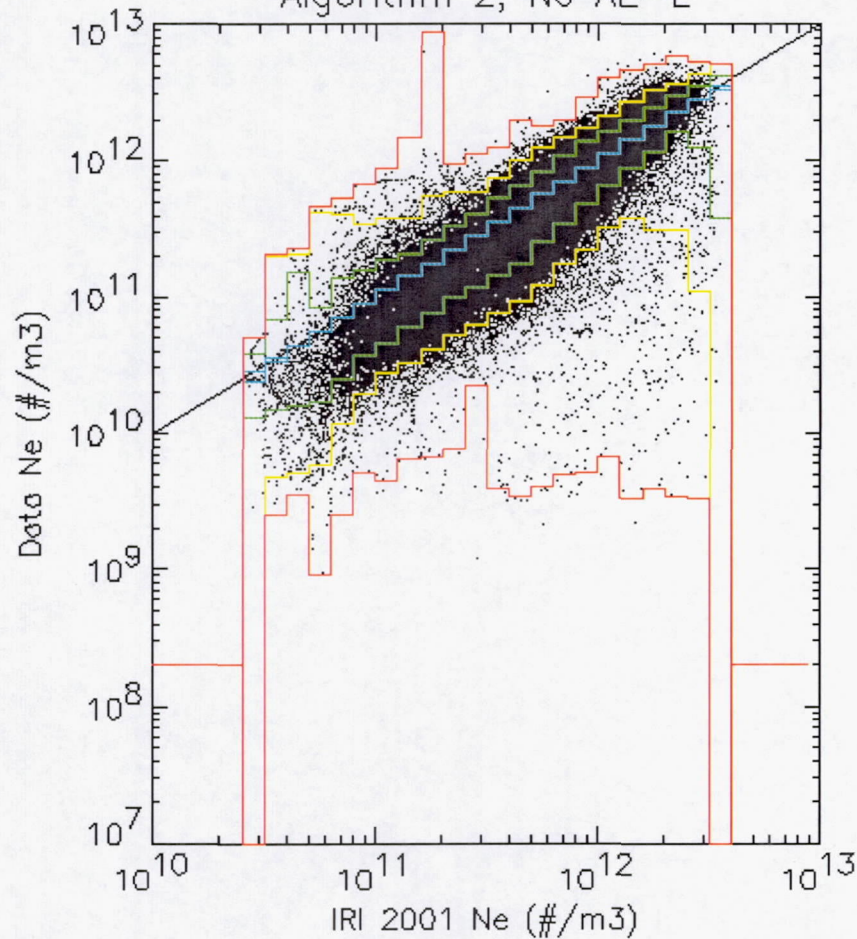
350 km < z < 450 km -51.6° ≤ latitude ≤ +51.6° SZA_{SR}(z)+10° < SZA_{SR}(z)



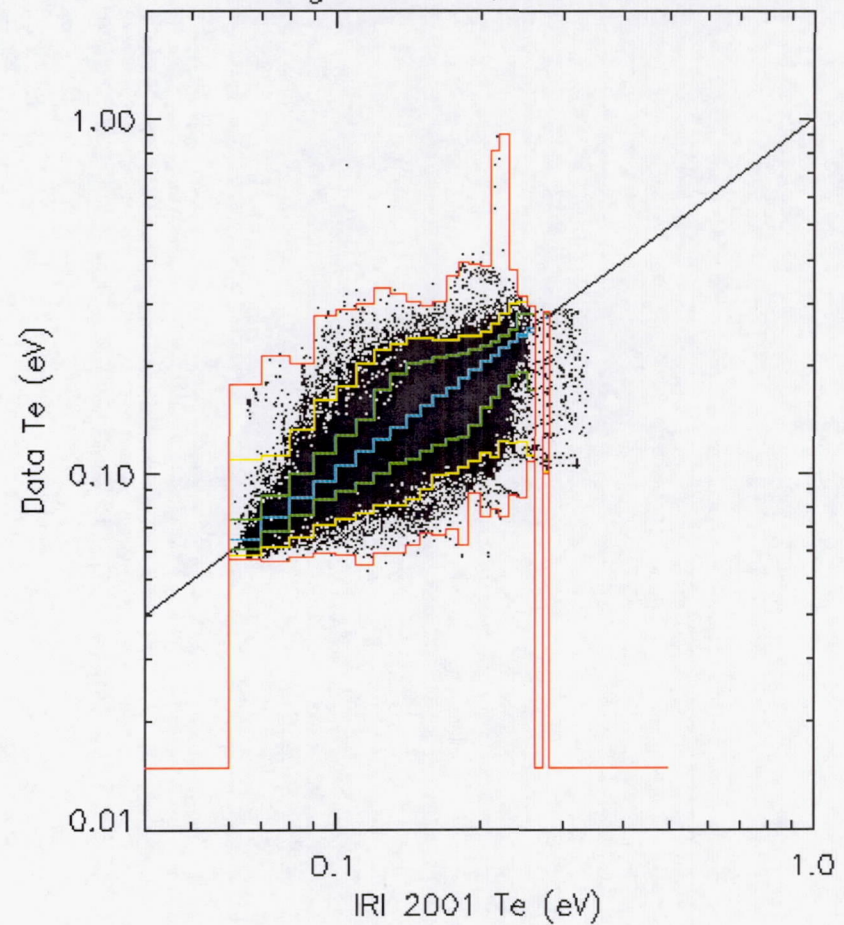
IRI vs Data

$|\text{lat}| < 51.6$ $350 \text{ km} < z < 450 \text{ km}$

Algorithm 2, No AE-E



Algorithm 2, No AE-E

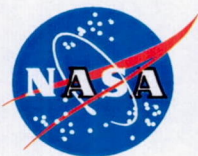


Blue: mean IRI value in bin

Green: +/- 68%

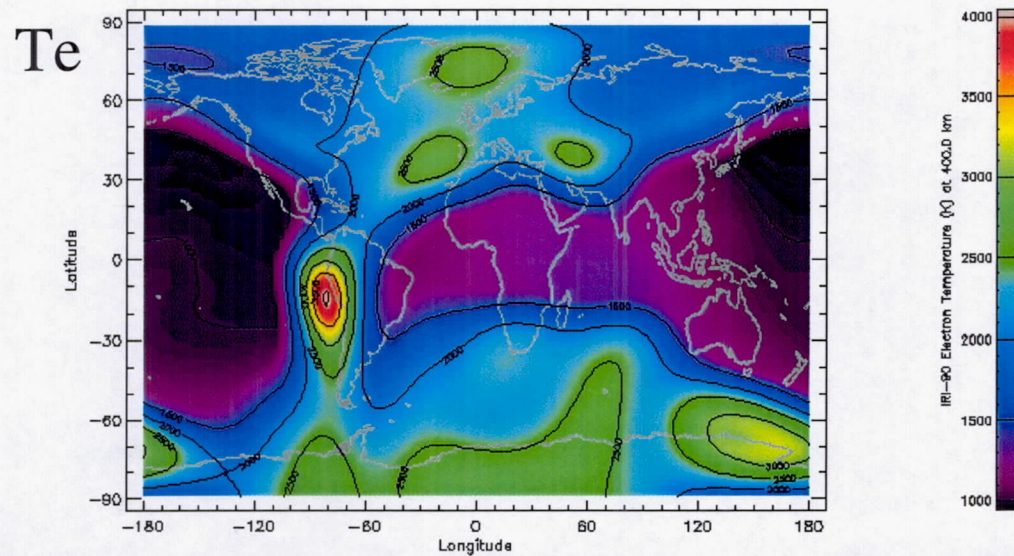
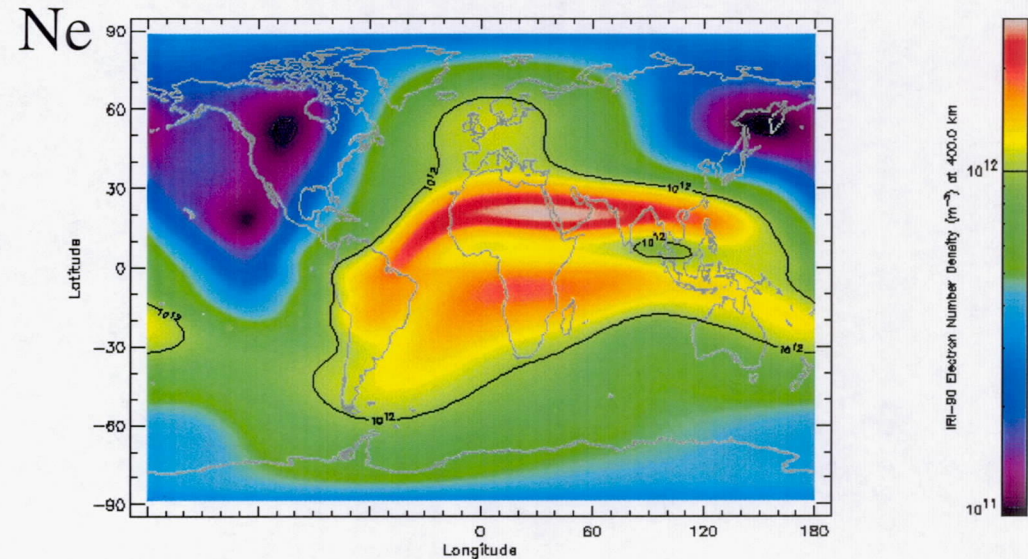
Yellow: +/- 95%

Red: +/- 99.9%

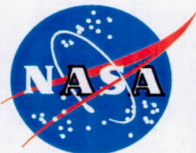


International Reference Ionosphere (IRI)

- Environment variability:
 - 13 month F10.7 (solar EUV proxy)
 - Ap (2000)
 - Climatological model
 - Not intended to reproduce individual events
- Diurnal, spatial variations



- Good for design studies
- Empirical model is fast



3 σ Calculation

- **Bin satellite data based on increments of corresponding IRI model Ne values (logarithmic bins)**
 - Within each bin, compute IRI Ne (or Te) in center of bin, $IRI = (IRI2 - IRI1)/2$
 - Compute total number of data points in bin = m
- **Divide data in bin into two populations:**
 - High Population: Data values > IRI Ne and Te within each bin
 - Low Population: Data values < IRI Ne and Te within each bin
- **Sequence all data point values (either Ne or Te) from lowest to highest = 1 to m**
- **Define data (Ne or Te) points in bin which are below IRI (Ne or Te)**
 - Number of points below IRI is 'n' and points range from 1 to 'n'
 - Point 'n' is highest data point (Ne or Te) which is less than IRI
- **Define data (Ne or Te) points in bin which are above IRI (Ne or Te)**
 - n+1 to m, where point n+1 has lowest value in upper bin above IRI
- **Computation of σ_1 , σ_2 , σ_3 are based on number of points:**
 - Compute upper bin σ_0 , σ_{1u} , σ_{2u} , σ_{3u} values ($\sigma_0 = 0$) from values at percentiles of 0%, 68%, 95%, and 99.9% for upper bin

σ_u	P = Point count from Bottom	$\delta Ne = Ne(P) - Ne(n+1)$	$\delta Te = Te(P) - Te(n+1)$
0	n+1	$\delta Ne(P)$	$\delta Te(P) = \sigma_{0u}'$
68%	$0.68(m-n)+n$	$\delta Ne(P)$	$\delta Te(P) = \sigma_{1u}'$
95%	$0.95(m-n)+n$	$\delta Ne(P)$	$\delta Te(P) = \sigma_{2u}'$
99.9%	$0.999(m-n)+n$	$\delta Ne(P)$	$\delta Te(P) = \sigma_{3u}'$



3 σ Calculation

– Computation of σ_1 , σ_2 , σ_3 are based on number of points (continued):

- Compute lower bin σ_0 , σ_{1u} , σ_{2u} , σ_{3u} values ($\sigma_0 = 0$) from values at percentiles of 0%, 68%, 95%, and 99.9% for lower bin

σ_l	P = Point count from Bottom	$\delta Ne = Ne(P) - Ne(n+1)$	$\delta Te = Te(P) - Te(n+1)$
0%	1.0(n)	$\delta Ne(P)$	$\delta Te(P) = \sigma_{0l}'$
68%	0.32(n)	$\delta Ne(P)$	$\delta Te(P) = \sigma_{1l}'$
95%	0.05(n)	$\delta Ne(P)$	$\delta Te(P) = \sigma_{2l}'$
99.9%	0.001(n)	$\delta Ne(P)$	$\delta Te(P) = \sigma_{3l}'$

– Final Table for each bin:

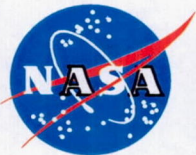
m,n Number of points for Ne and Te

IRI (Ne or Te)

σ values for Ne or Te

σ_{0u}	σ_{0l}
σ_{1u}	σ_{1l}
σ_{2u}	σ_{2l}
σ_{3u}	σ_{3l}

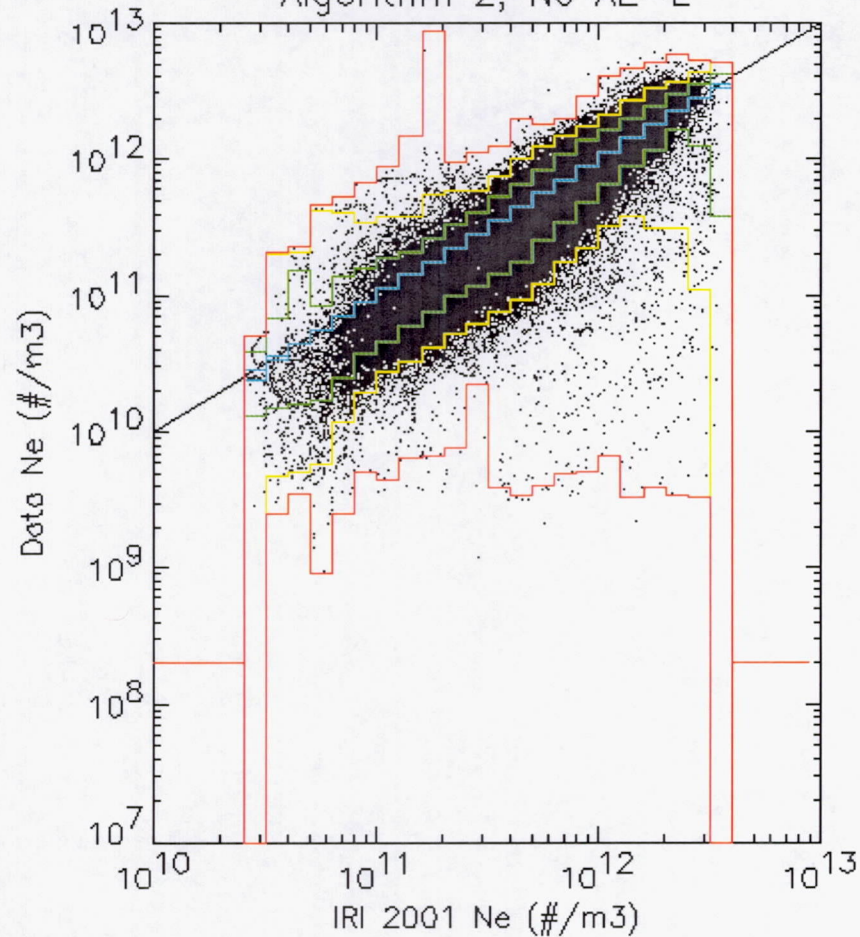
– Variability is Ne or Te = IRI + σ



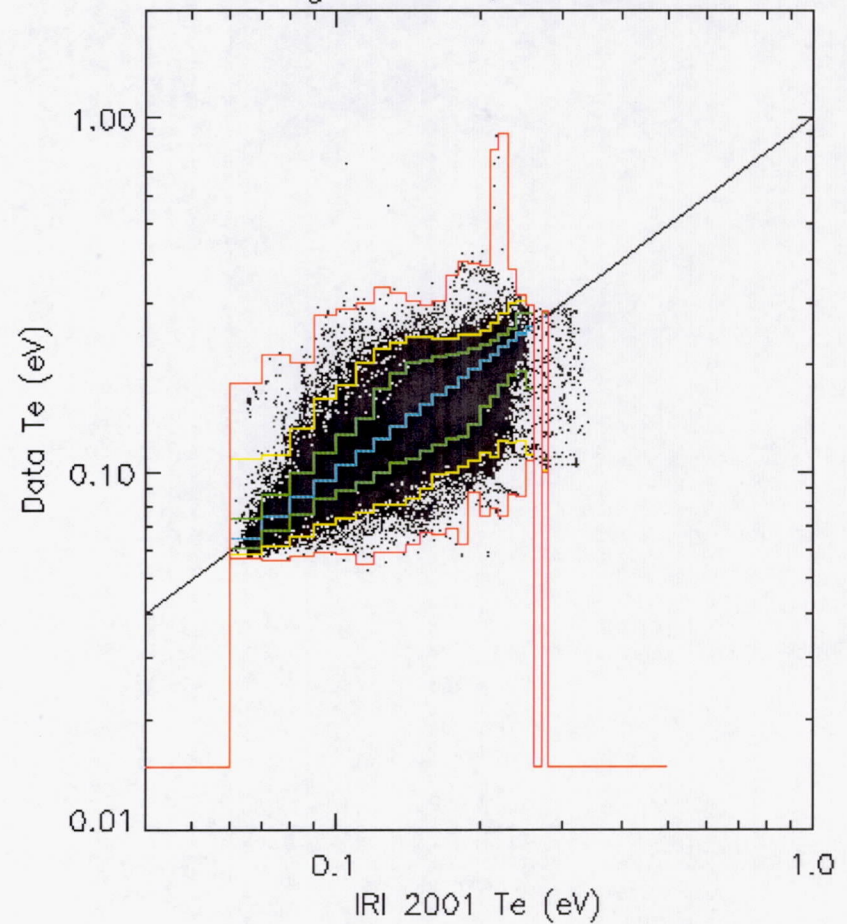
IRI vs Data

$|\text{lat}| < 51.6$ $350 \text{ km} < z < 450 \text{ km}$

Algorithm 2, No AE-E



Algorithm 2, No AE-E

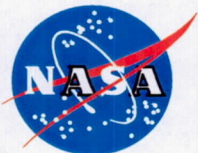


Blue: mean IRI value in bin

Green: +/- 68%

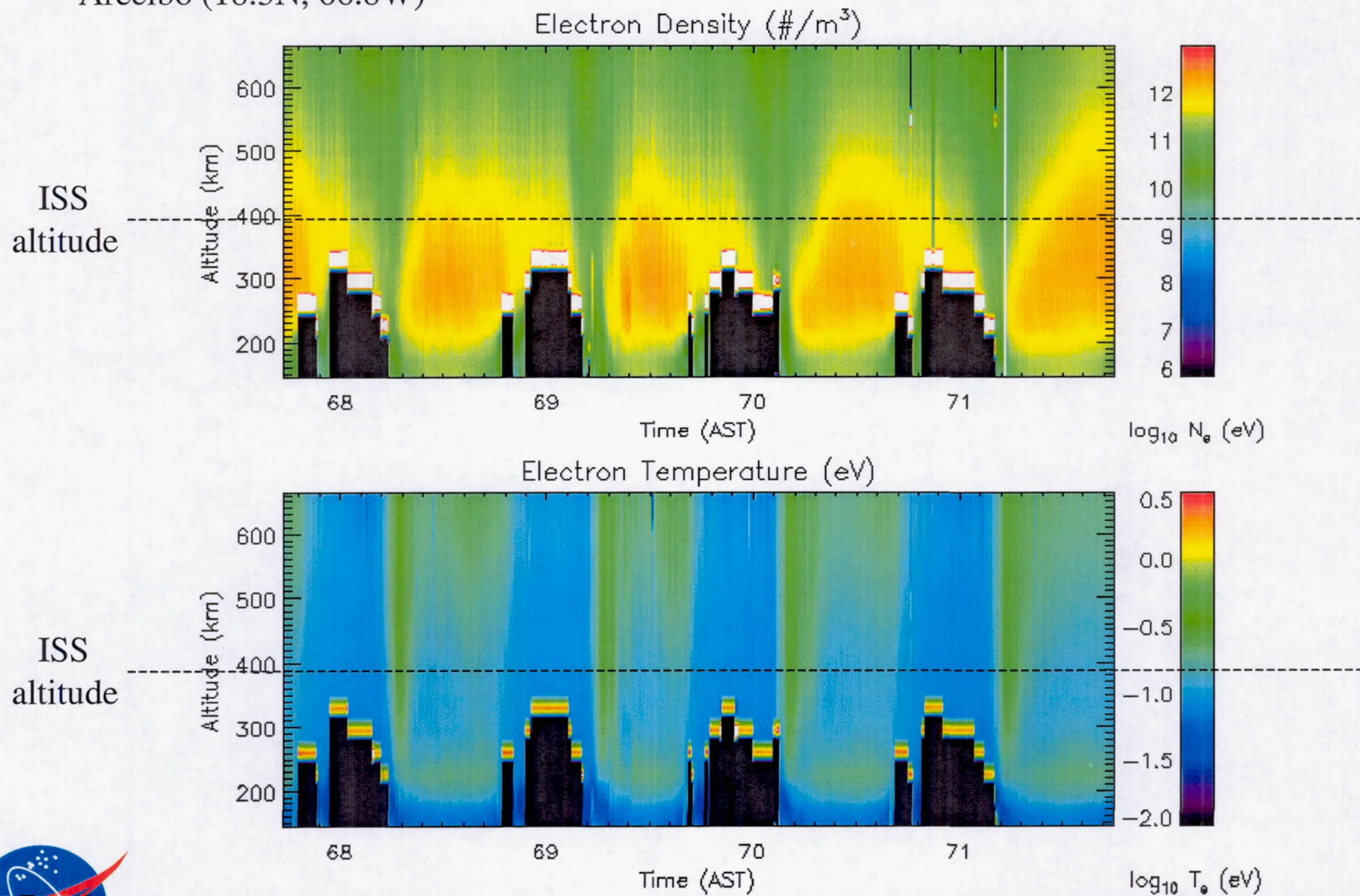
Yellow: +/- 95%

Red: +/- 99.9%

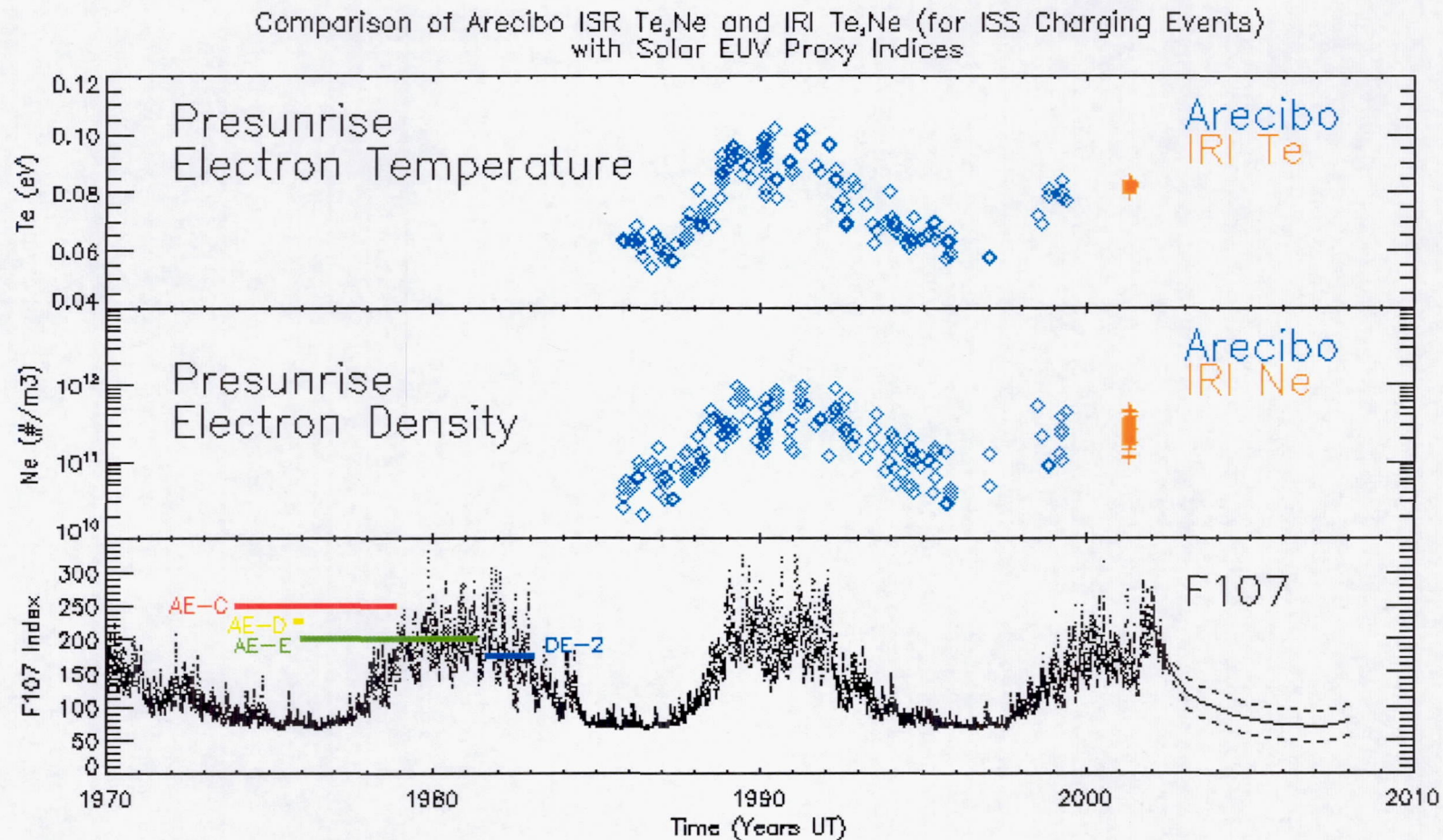


Eclipse Exit Te

Arecibo (18.3N, 66.8W)



Solar Cycle Variations of Eclipse Exit Te

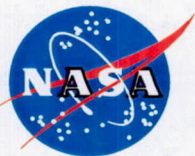
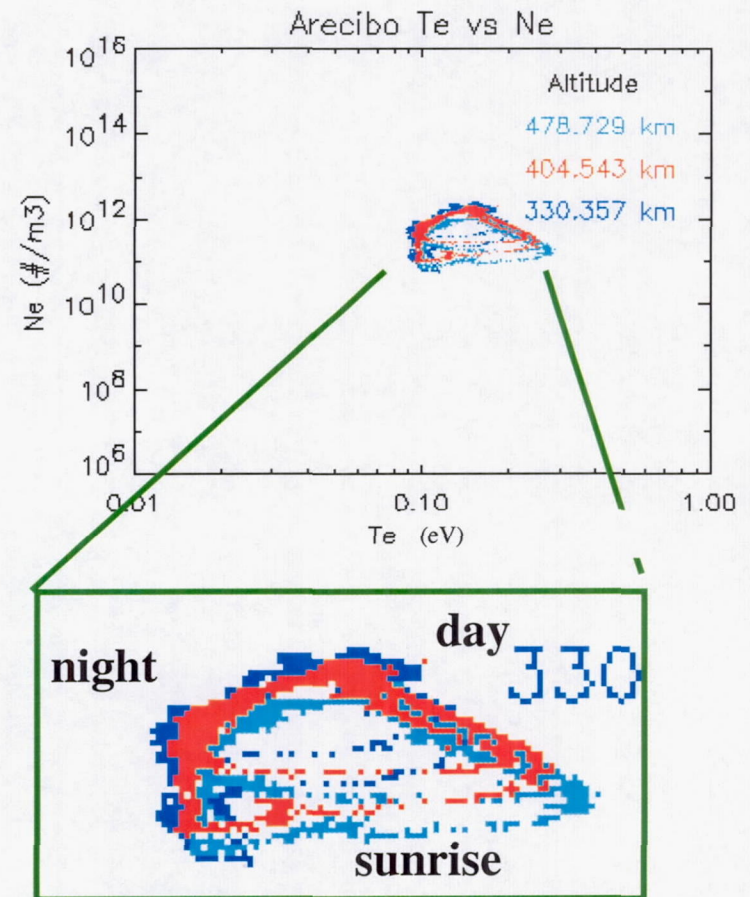
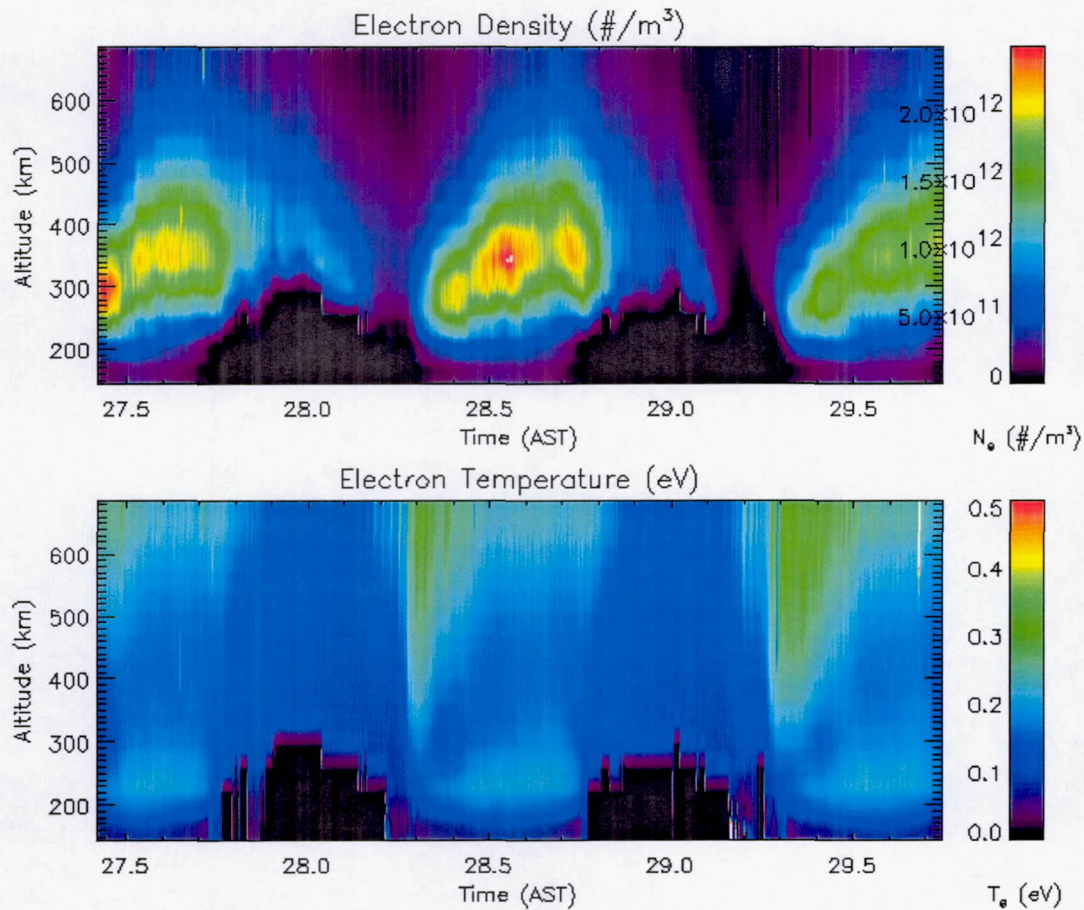


[from Mikatarián et al., 2002]



Ne, Te Correlation

Arecibo losF920127.c9



Current work

– New data

– Discussion

- Documentation**
- 3 sigma**
- Schedule**



Old Data

Satellite Data (in house)

AE-C	150 km	x	4300 km	x	68.1 deg
AE-D	154 km	x	13816 km	x	90.1 deg
AE-E	156 km	x	2983 km	x	90.1 deg
DE 2	300 km	x	1000 km	x	90 deg

Incoherent Scatter Radar Data (in house)

Arecibo (T/R)	18.3N	-66.8E	85-99
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New Data

Satellite Data (in house)

AE-C	150 km	x	4300 km	x	68.1 deg
AE-D	154 km	x	13816 km	x	90.1 deg
AE-E	156 km	x	2983 km	x	90.1 deg
DE 2	300 km	x	1000 km	x	90 deg
Explorer 22	889 km	x	1081 km	x	79.7 deg
Explorer 31	500 km	x	3000 km	x	79.8 deg
Aeros-A	223 km	x	867 km	x	96.9 deg
Alouette 2	505 km	x	2987 km	x	79.8 deg
Aureol 3	380 km	x	1920 km	x	82.6 deg
Hinotori	548 km	x	603 km	x	31.3 deg
ISIS-1	578 km	x	3526 km	x	88.42 deg

Satellite Data (in process)

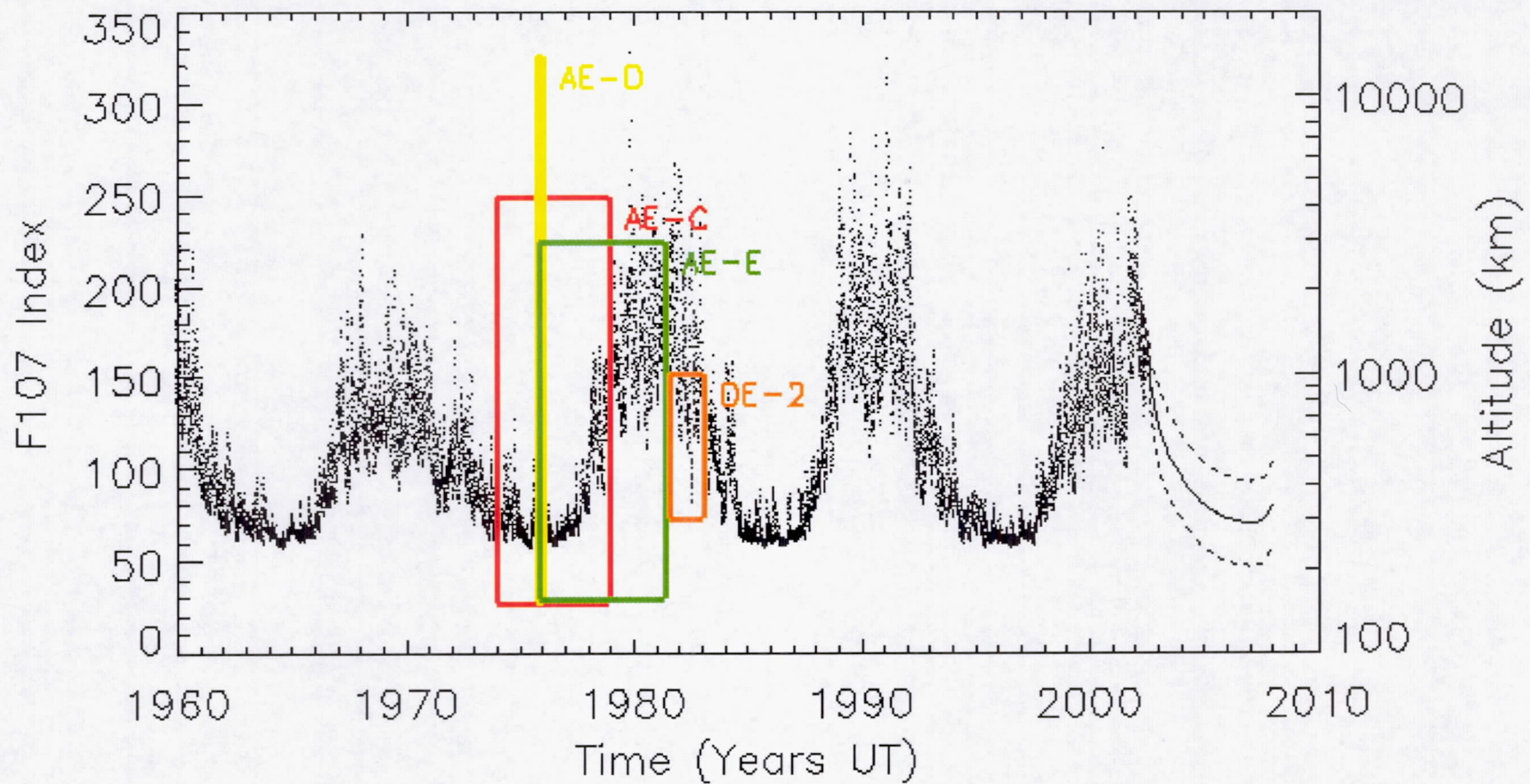
DMSP	835 km	x	835 km	x	98.2 deg
	– 2000, 2001, 2002 in house				
	– 1998, 1999 ready for downloading				
CHAMP	454 km	circular			x 87 deg
	– AFRL is reprocessing using updated algorithms, available ~August 2003				

Incoherent Scatter Radar Data (in house)

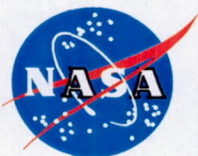
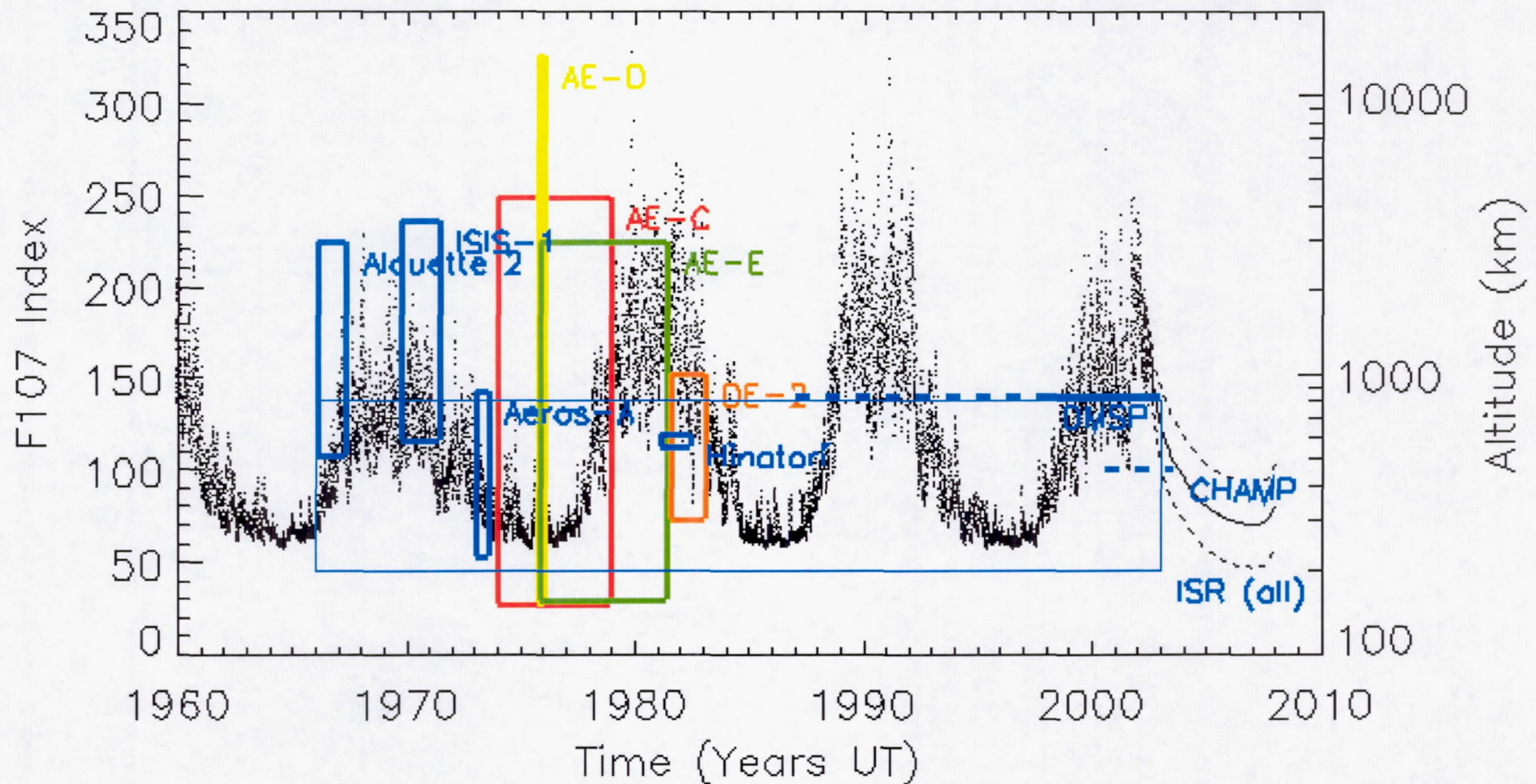
Arecibo (T/R)	18.3N	-66.8E	66,71-00
St. Santin (T)	44.6N	2.2E	66-86
--Nancay (R)	47.4N	2.2E	
--Mende (R)	44.5N	3.45E	
--Monpazier (R)	44.7N	0.8E	
Millstone Hill (T/R)	42.6 N	-71.5E	78-00
Jicamarca (T/R)	-11.95N	-76.0E	66,86,99-00
Irkutsk (T/R)	52.85N	103.1E	99-02
Karkov (T/R)	50.0N	36.2E	02
Chatanika (T/R)	65.1N	147.4W	76-81
Sondrestrøm	67.0 N	-51.0E	83-02
EISCAT, Tromsø (T/R)	69.6 N	19.2E	84-99
--Kiruna, Sweden (R)	67.87N	20.43E	
--Sodankylä, Finland (R)	67.37N	26.63E	
EISCAT, Svalbard (T/R)	78N	15.7E	98



Old Database



New Database



Forward Work

- **Satellite data analysis**
 - Complete acquisition of DMSP, CHAMP data
 - Complete processing satellite data holdings into study sets
 - Incorporate new data into statistics
 - Re-derive $n\sigma$ statistics
 - Both original Ne, Te independent values
 - [Ne,Te] correlated statistics.....e.g., explore statistics of (Ne/Te) or similar parameters
- **Incoherent scatter radar data analysis**
 - Data
 - Process from CEDAR Database CBF format to ascii (complete)
 - Process ascii to study sets (in process)
 - Modify analysis software to include radar data
 - Incorporate ISR data into statistics
 - Re-derive $n\sigma$ statistics for ISR data
 - Other
 - Contact PI's for radar data (obligation of using CEDAR Database)
 - MU radar data?
 - CEDAR lists velocity data, but no NTV, <500 km.
 - Contact S. Fukao (PI).
 - Check CEDAR database for updated files (B. Emory/HAO indicated new data, May 2003)



Forward Work

- **Variability Model**

- Provide updated variability model to Boeing
 - Do we want options for statistics of (1) satellites, (2) ISR, and (3) both?
- Coordinate model format with H. Barsamian for ease of incorporation into PIM

- **Documentation**

- Write report documenting data analysis, results
 - Analysis of satellite, radar data
 - Geophysical conditions that may yield high Ne, low Te (input from S. Koontz).
- Peer review
 - Submit publications describing variability work to peer reviewed journal (with working group as co-authors)
 - Presentation at Spacecraft Charging conference?
 - Invitation to present variability work at 2003 International Reference Ionosphere Workshop (October 2003)
 - Papers published in Advances in Space Research



Review of Ground Based Radar Low Electron Temperatures

ISS Plasma TIM
Huntsville, AL 28-30 May 2003

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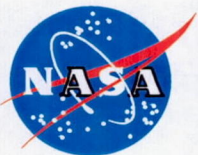


Overview

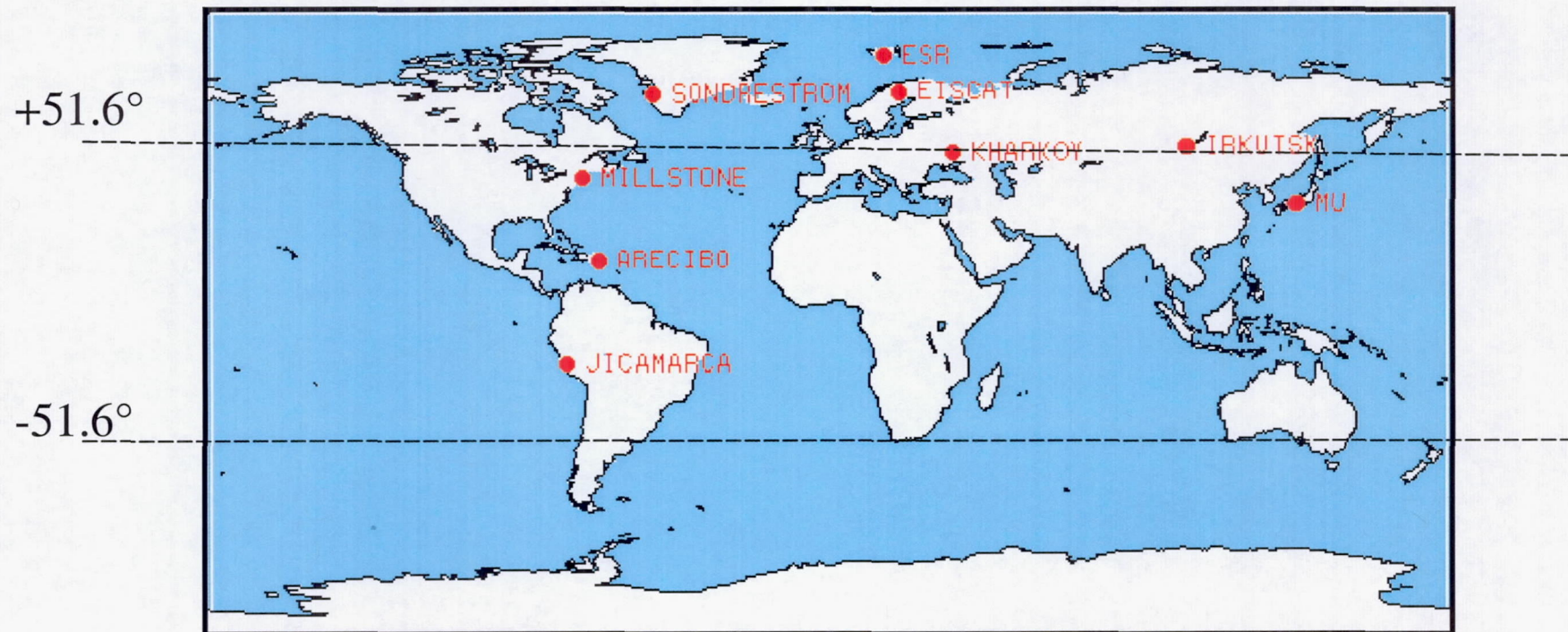
- **Ground based radar**
 - Sites, database
 - Examples
 - Comparison with FPMU data
- **Low electron temperature discussion**



Review of Ground Based Radar Data



ISR Sites

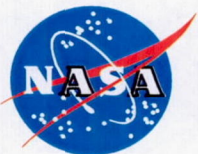


- 6 sites within $\pm 51.6^\circ$ latitude
- NSF facilities at Millstone, Arecibo, Jicamarca best opportunity for our use



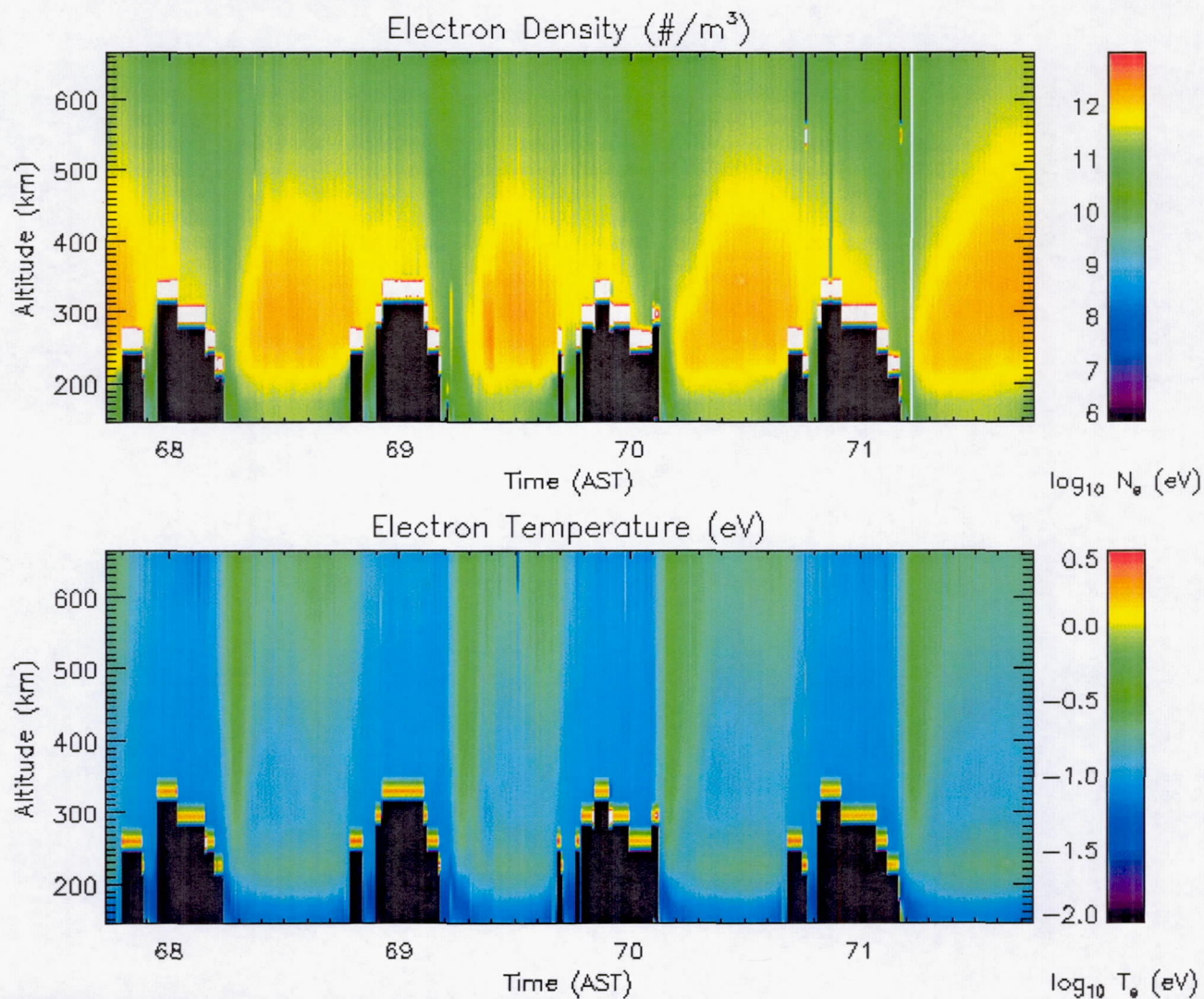
Operational ISR Sites

Site	Lat	Lon	Type	Contact
Jicamarca, Peru	-11.95	-76.0	ISR	Kudeki/Hysell
Arecibo, Puerto Rico	18.3	-66.8	ISR	Q. Zhou
Millstone Hill, Massachusetts	42.6	-71.5	ISR	Foster/Zhang
Kharkov, Ukraine	50.0	36.2	ISR	V. Taran
Irkutsk, Russia	52.85	103.1	ISR	G. Zherebtsov
Sondrestrom, Greenland	67.0	-51.0	ISR	J. Thayer
EISCAT Sodankyla, Finland	67.4	26.6	ISR	A. Van Eyken
EISCAT Kiruna, Sweden	67.9	20.4	ISR	A. Van Eyken
EISCAT Tromso, Norway	69.6	19.2	ISR	A. Van Eyken
EISCAT Svalbard (ESR), Norway	78.2	15.7	ISR	A. van Eyken
MU, Japan	34.8	136.1	ISR	S. Fukao



Arecibo (18.3N, 66.8W) Ne, Te

Arecibo losF990308.c9



AST=Atlantic Standard Time = UT - 4 hrs



Millstone Hill ISR-ISS Geometry

Elevation scan:

North: $+7^{\circ}$ az

$+4^{\circ}$ el

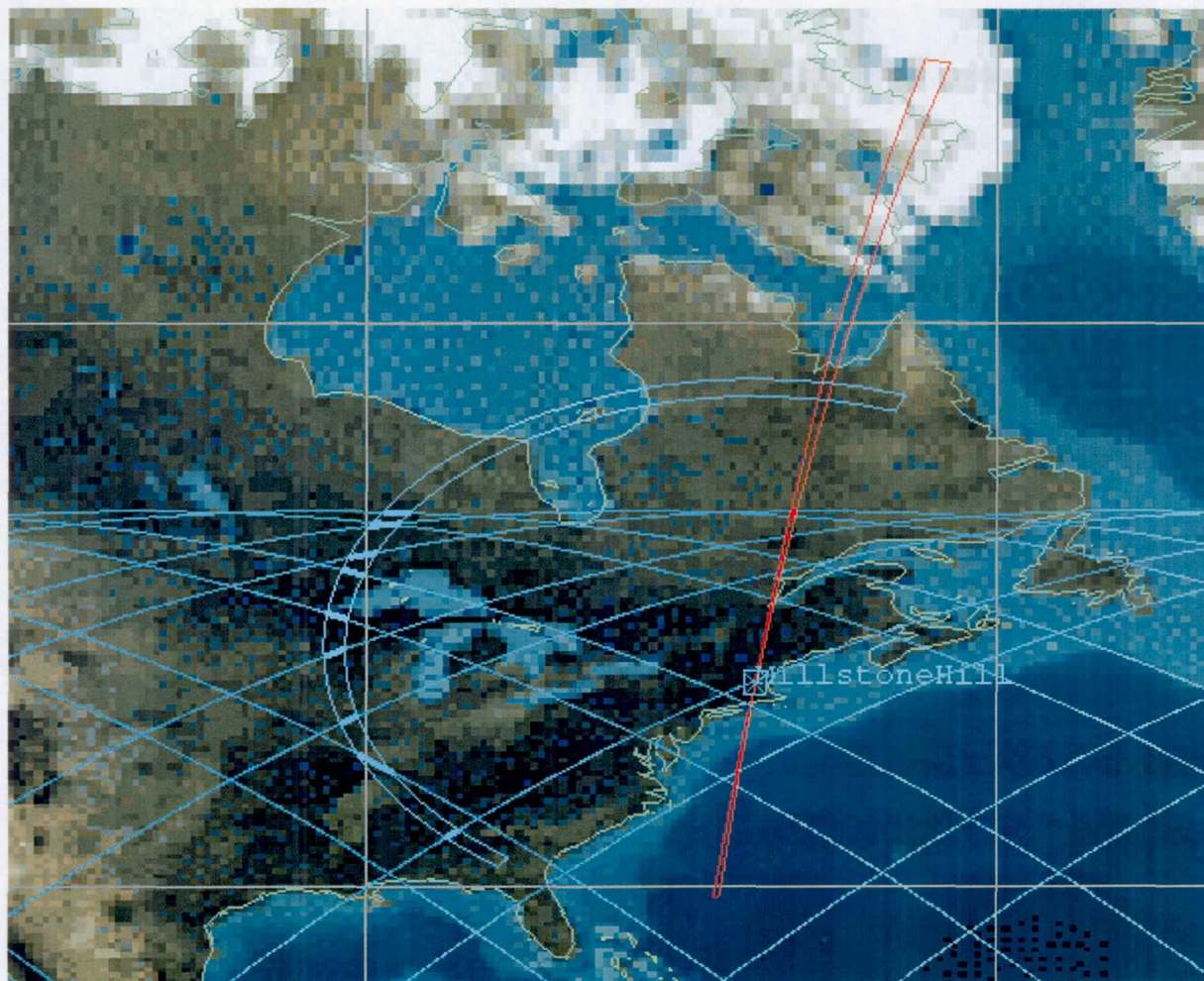
South: $+187^{\circ}$ az

$+25^{\circ}$ el

Azimuth scan:

$+6^{\circ}$ el

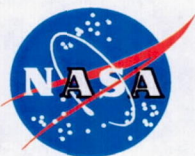
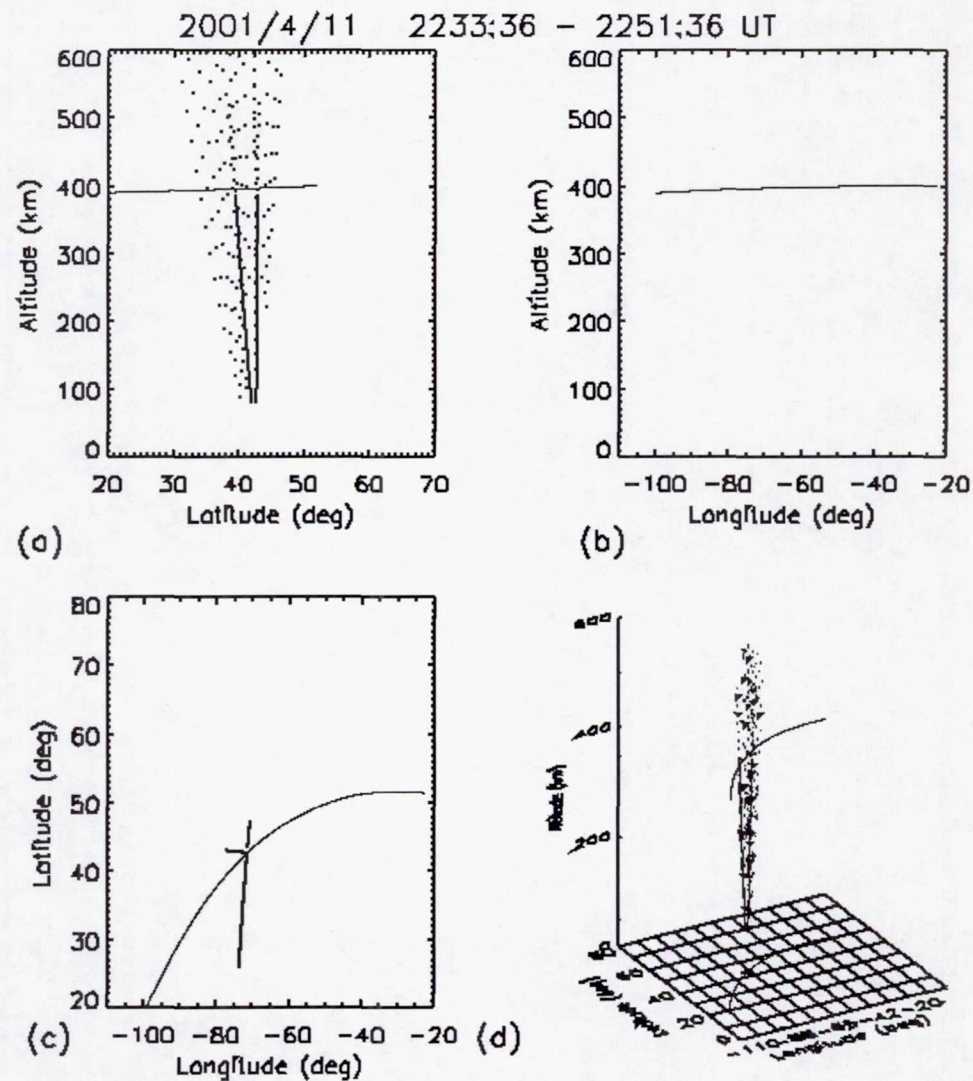
-135° to $+15^{\circ}$ az



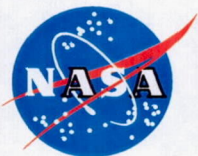
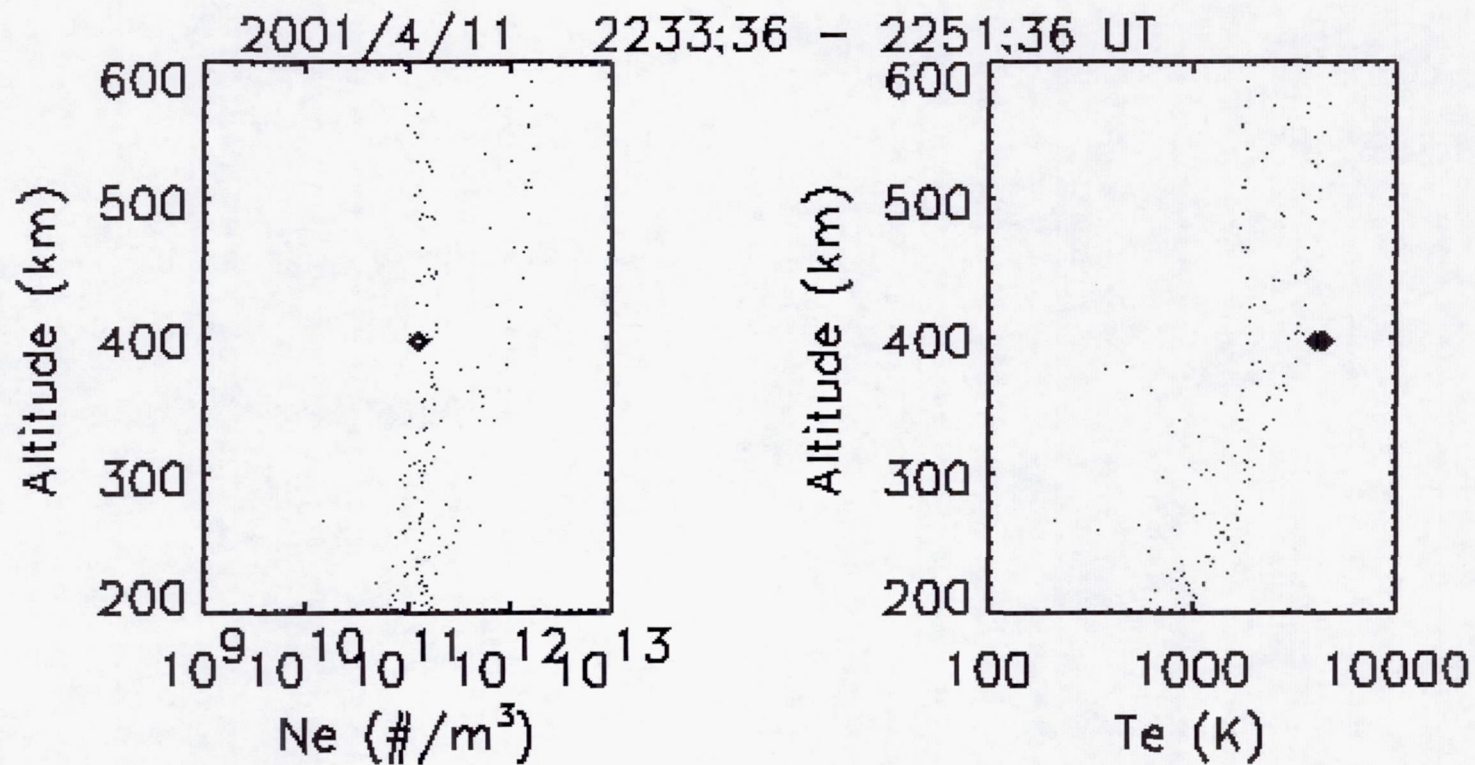
11/04/2001 12:00 UT to 13/04/2001 06:00 UT



11 Apr 22:42:39 UT
(close approach time)



11 Apr 22:42:39 UT

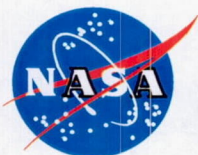
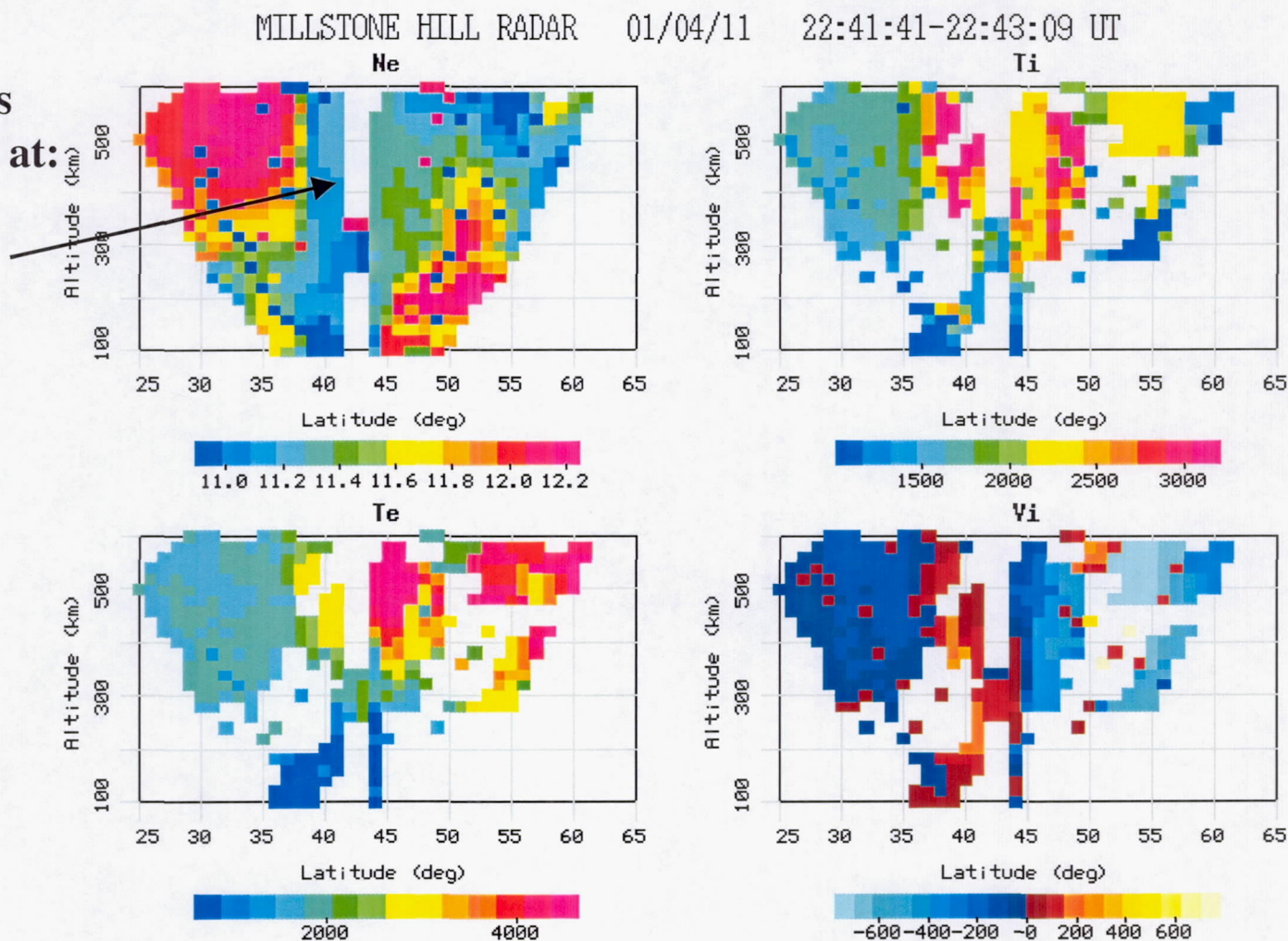


11 Apr 22:42:39 UT

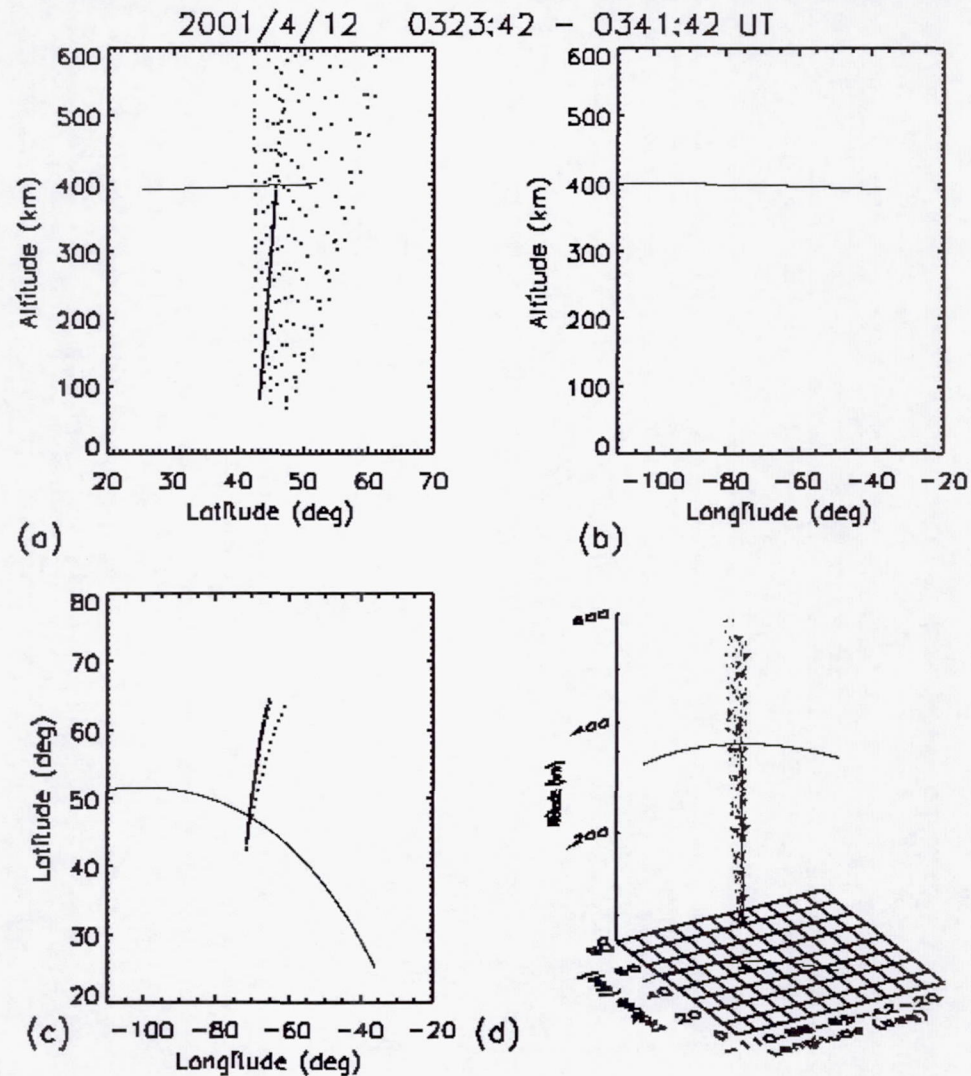
ISS intersects
elevation scan at:

42.8°N

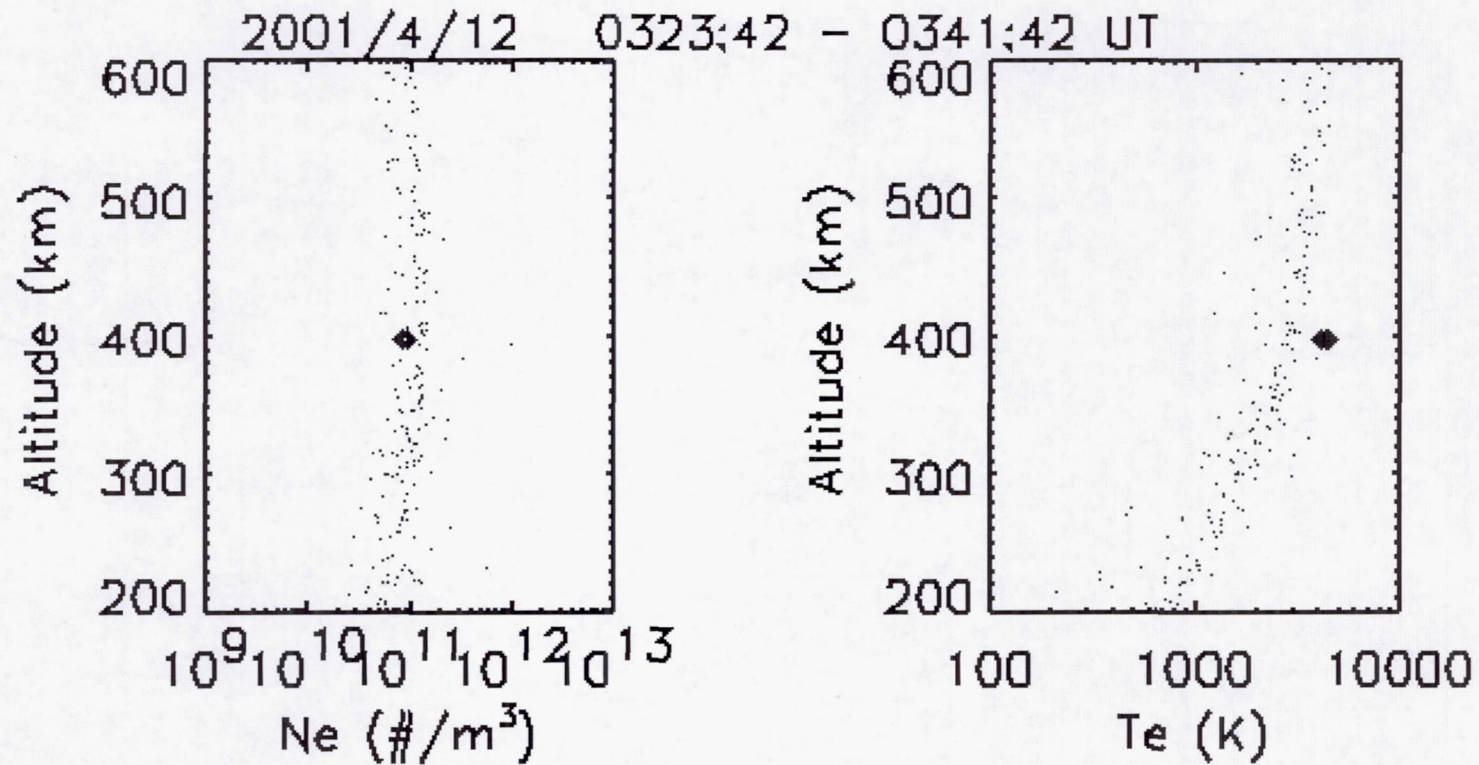
398.0 km



12 Apr 03:29:00 UT



12 Apr 03:29:00 UT



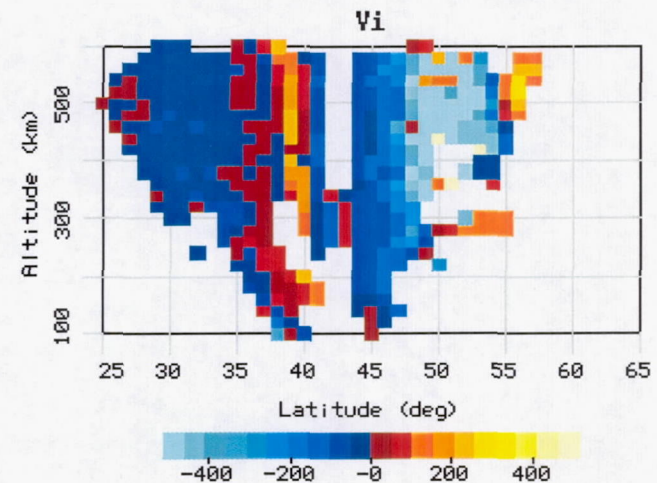
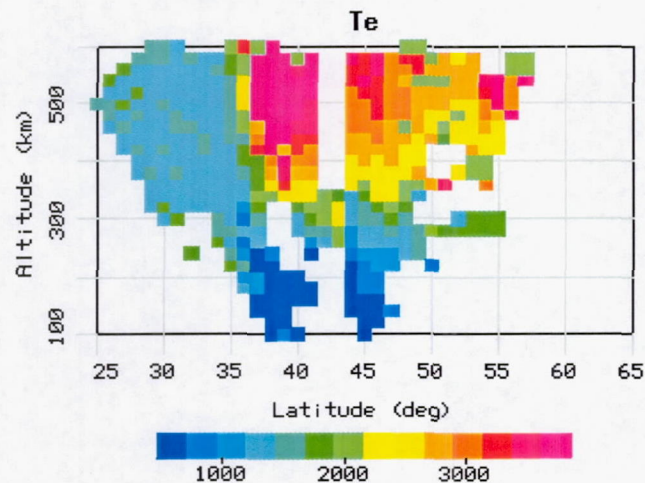
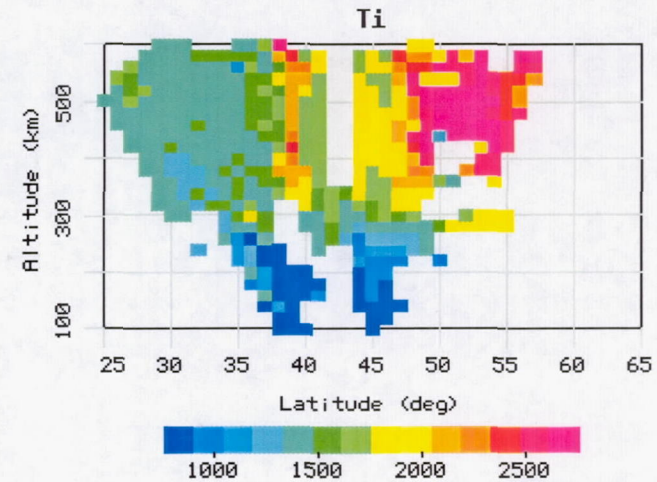
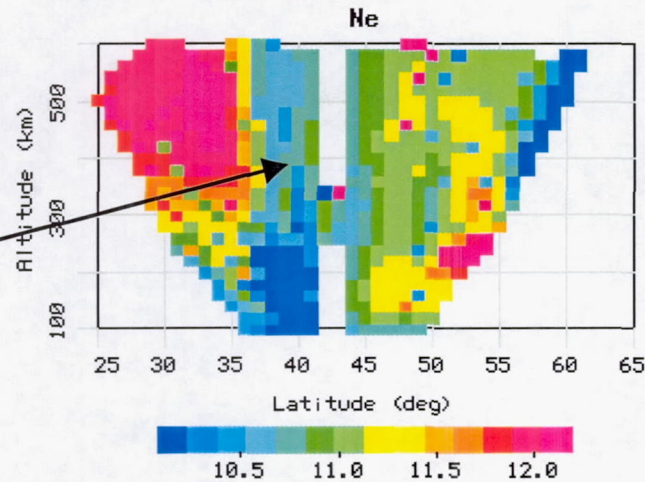
12 Apr 03:29:00 UT

MILLSTONE HILL RADAR 01/04/12 03:17:49-03:19:33 UT

ISS intersects
elevation scan at:

47.2°N

399.1 km



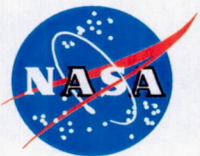
Statistical Comparisons of FPP and ISR Results

Encounter Date/Time		FPP		ISR		FPP		ISR	
		Ne	σ_{Ne}	Ne	σ_{Ne}	Te	σ_{Te}	Te	σ_{Te}
		(#/m ³ x10 ¹¹)				(K)			
ΔT_{ISR} : 18 min	ΔT_{FPP} : 9.6 min	$\chi^2 \leq 0.05$							
2001/4/11 2233:36 - 2251:36 UT		3.58	5.09	3.32	3.93	4087	665	1730	1067
2001/4/12 0006:36 - 0024:36 UT		19.00	4.69	25.88	142.21	2709	351	2989	1884
2001/4/12 0143:48 - 0201:48 UT		0.94	0.29	3.08	8.10	3533	328	2453	1482
2001/4/12 0323:42 - 0341:42 UT		1.26	0.98	1.03	1.21	3402	1019	2202	1680
2001/4/12 0500:00 - 0518:00 UT		1.87	1.47	0.79	0.42	2708	718	2104	1523
2001/4/13 0043:48 - 0101:48 UT		6.50	6.25	2.91	2.04	3028	631	1651	794
2001/4/13 0224:00 - 0242:00 UT		5.70	4.40	1.72	1.05	2378	427	1532	941
2001/4/13 0401:48 - 0419:48 UT		3.56	2.06	1.31	0.79	2111	193	2218	839

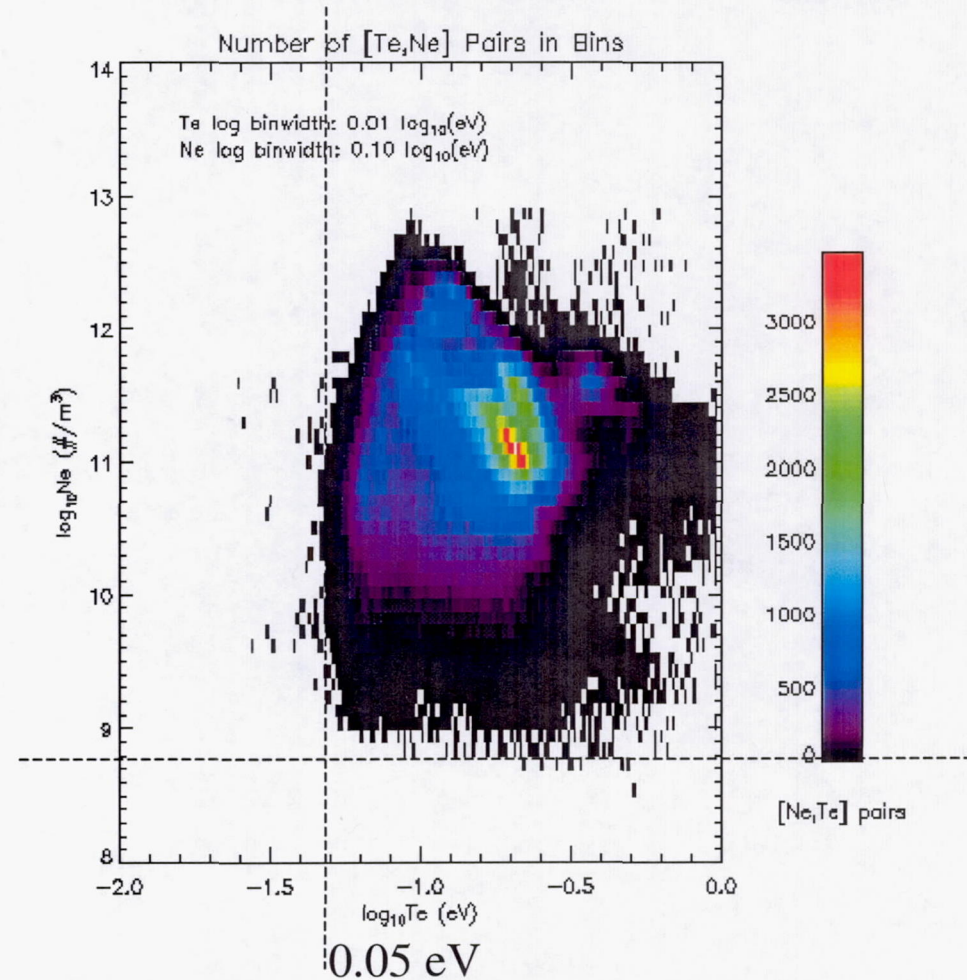
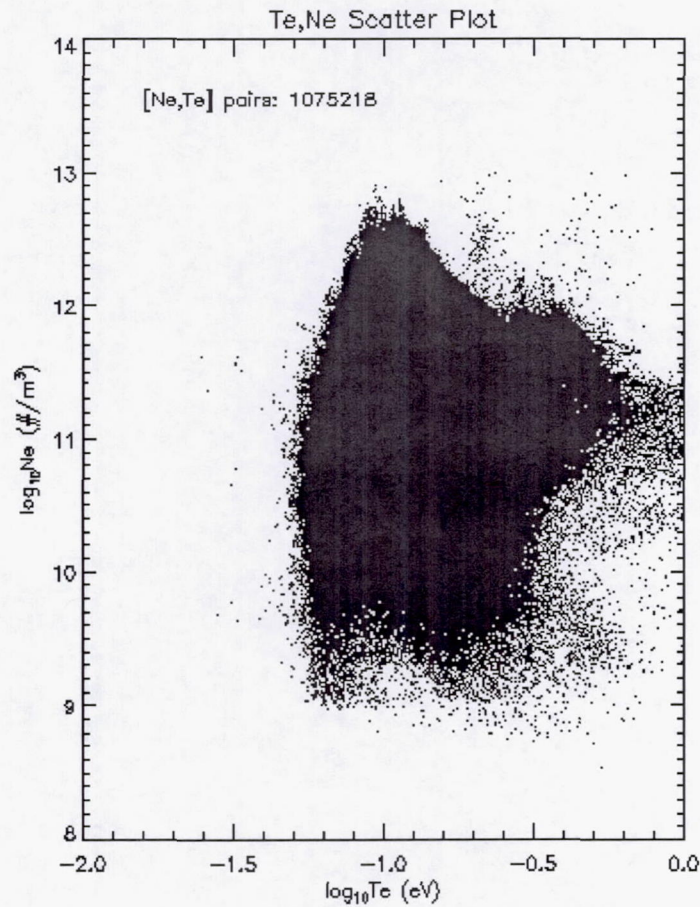
Reanalysis of this data in process.....



Low Electron Temperature Discussion



Ne, Te Scatter Plots



$\sim 1.07 \times 10^6$ values



$200 \text{ km} < z < 1000 \text{ km}$

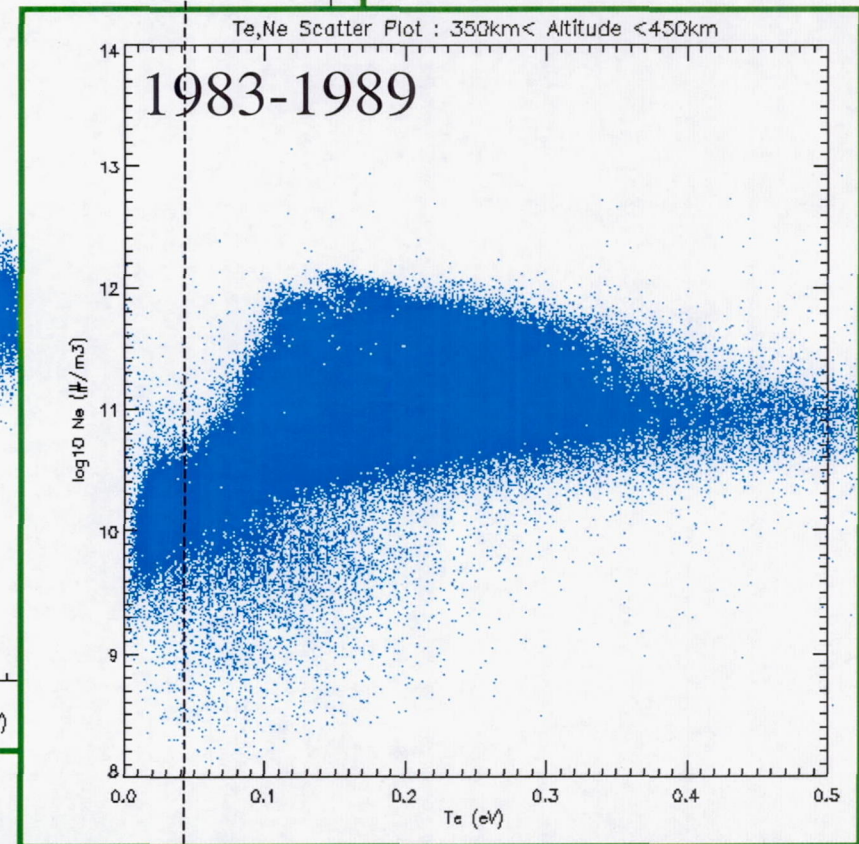
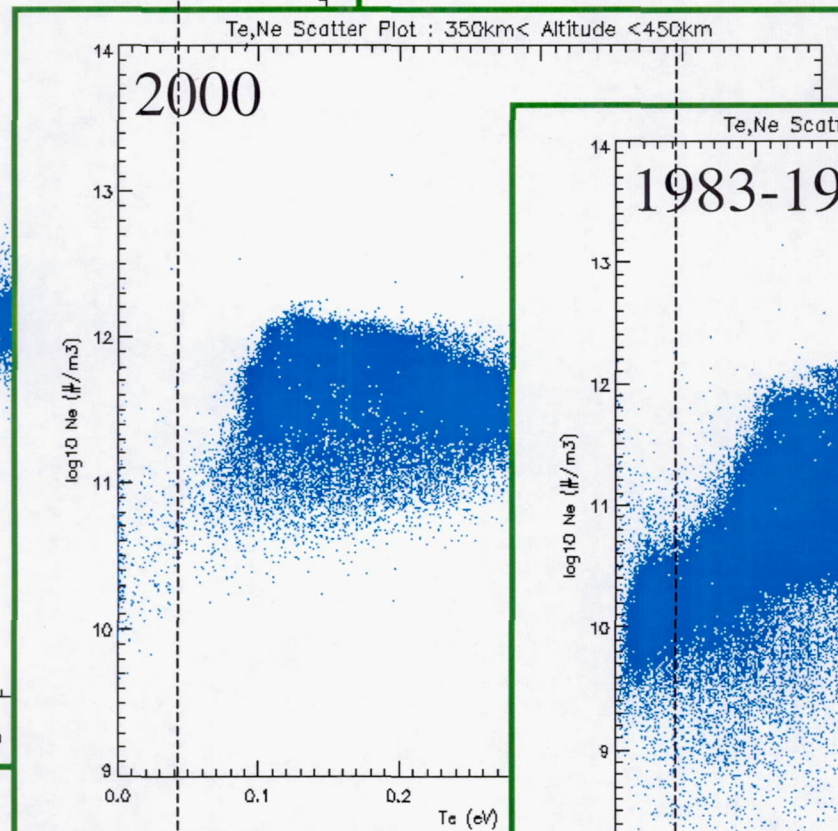
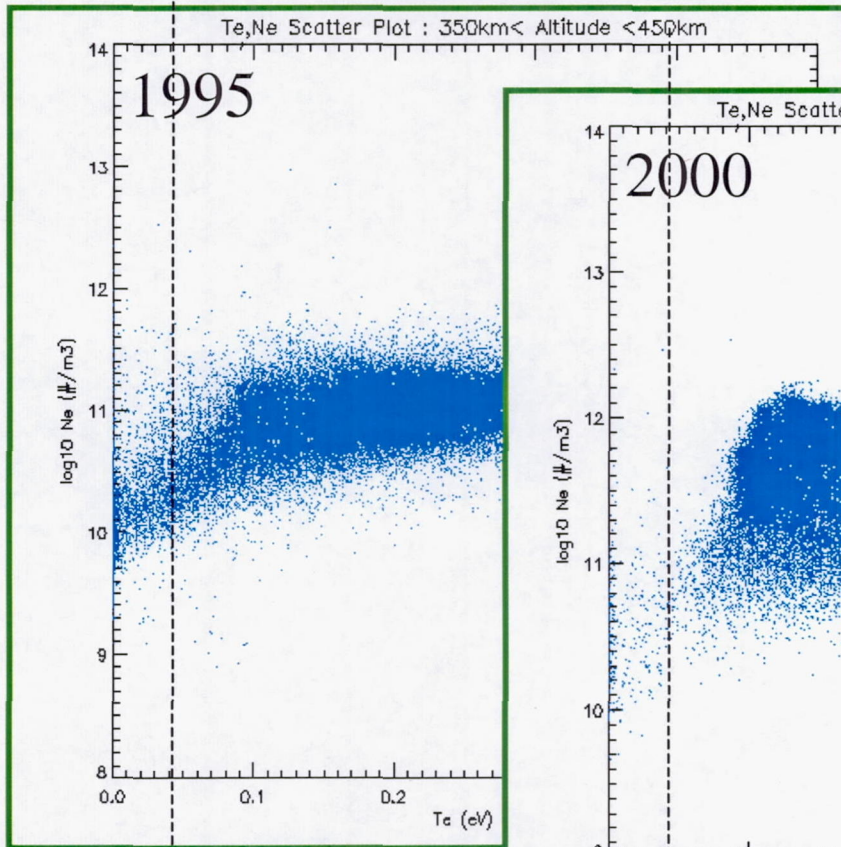
$-90.0^\circ \leq \text{latitude} \leq +90.0^\circ$

$0^\circ < \text{SZA} < 180^\circ$



Low radar Te values

Sondrestrøm, Greenland (67°N)

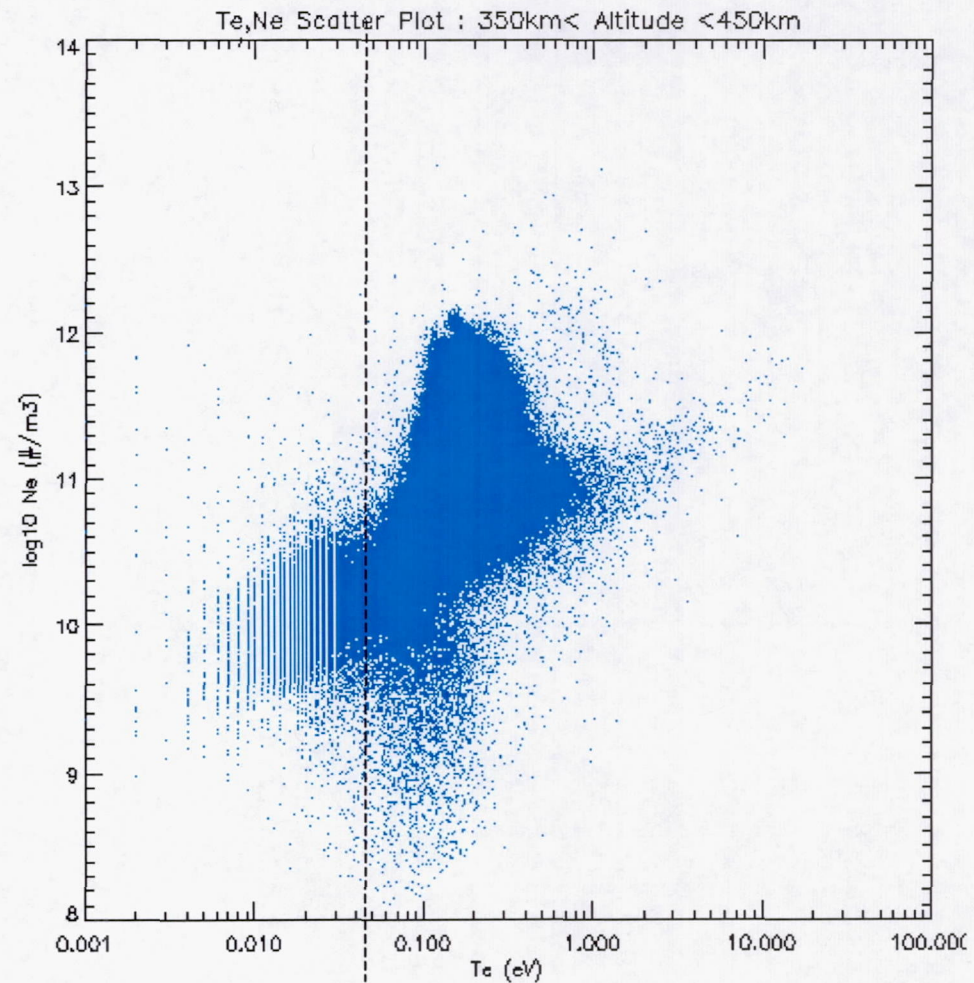


Note $T_e < 0.05$ eV



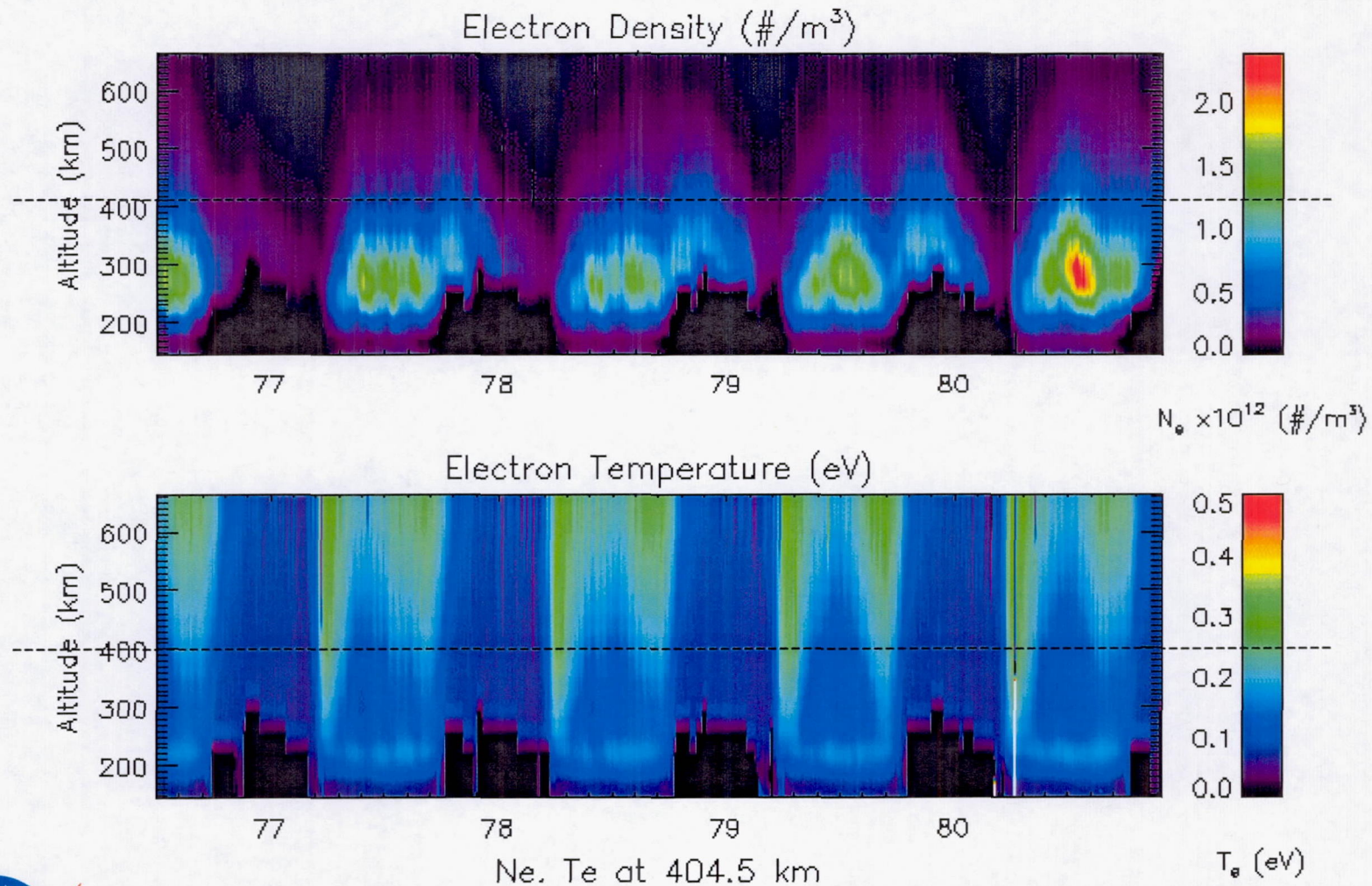
ISR Survey Data

Sondrestrom,
Greenland
1980's



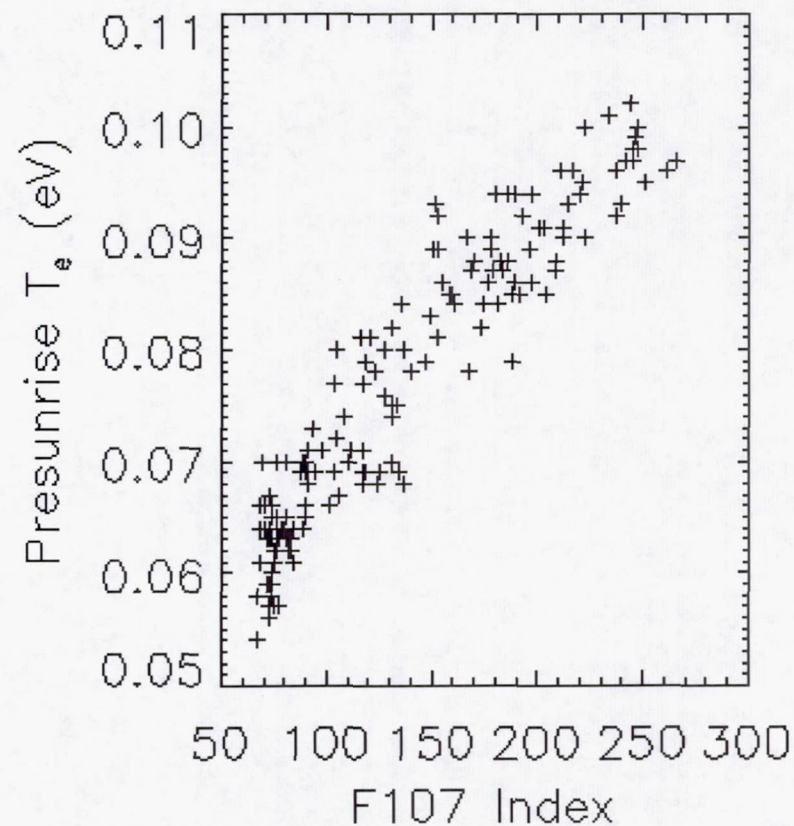
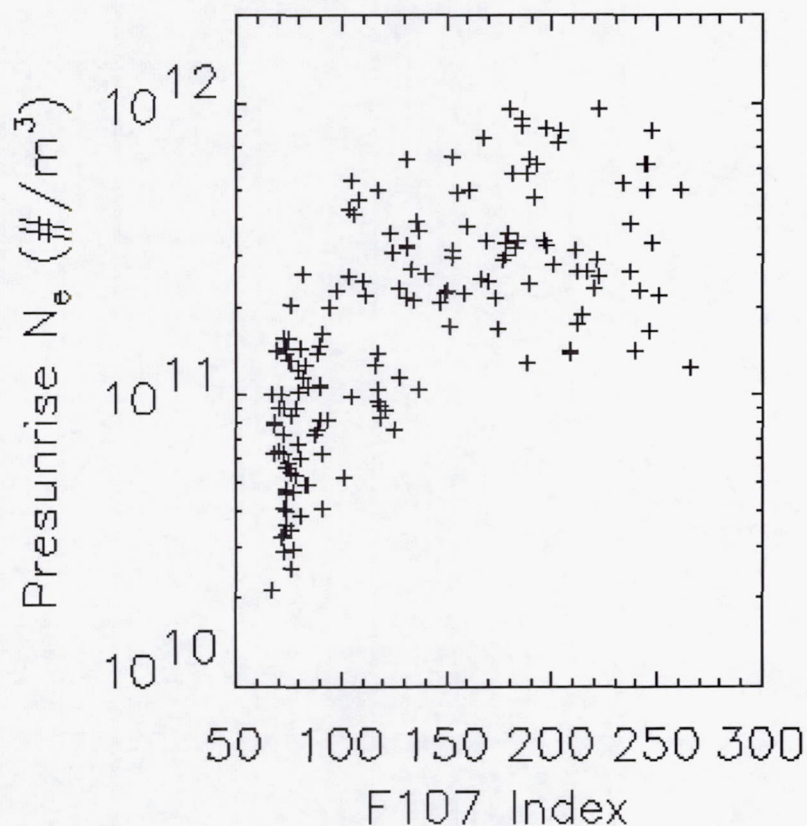
Arecibo (18°N) Ne, Te

Arecibo losF880316.c9

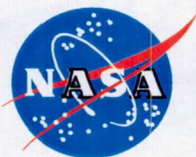




Presunrise ISR Ne, Te Variation with $F_{10.7}$

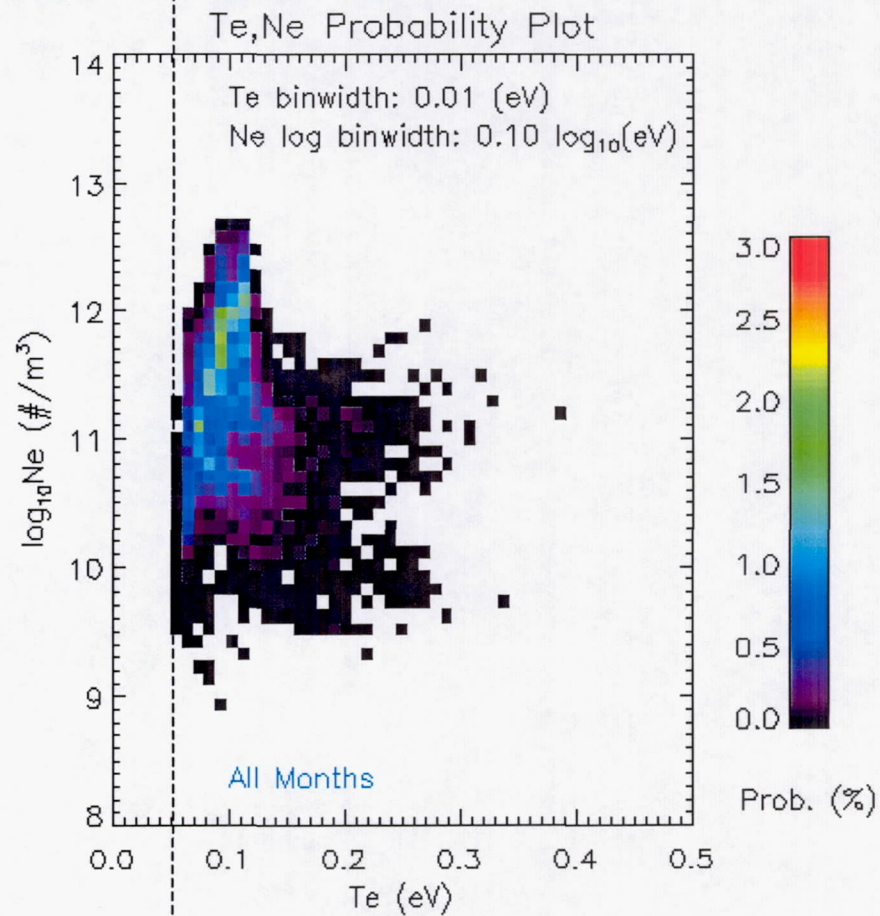
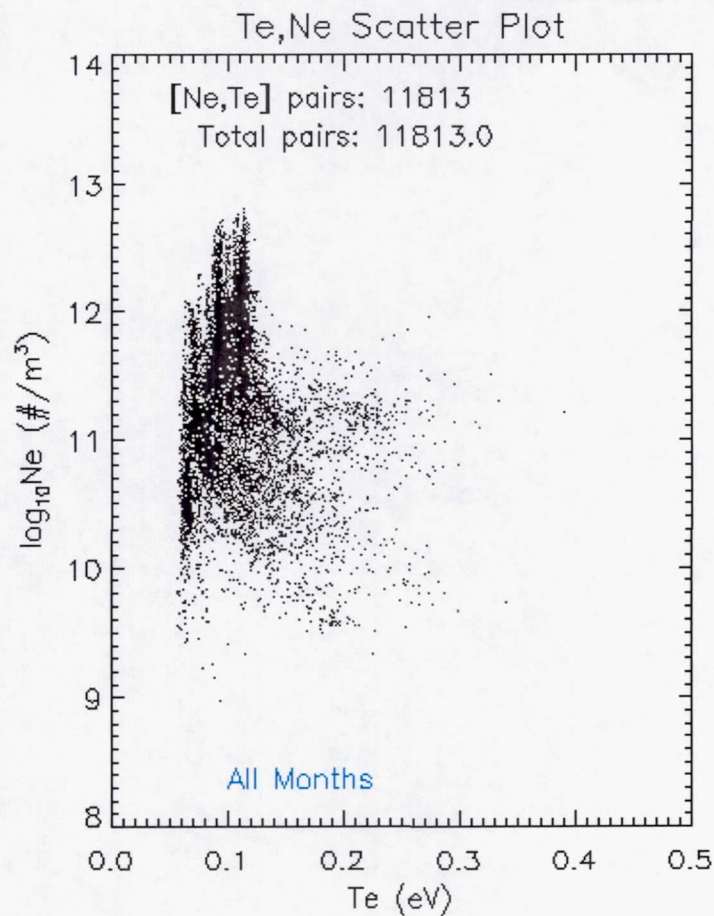


[from Mikatariian et al., 2002]



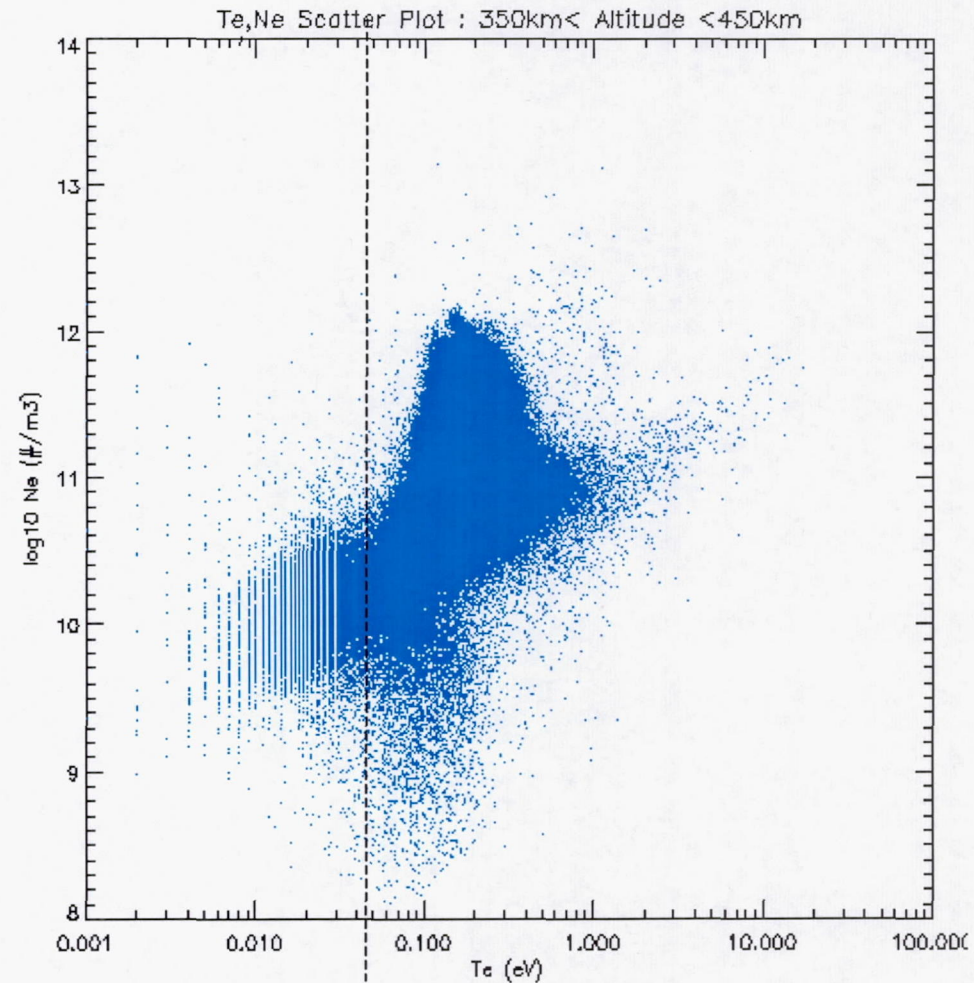
ISS Filtered Ne, Te Records

-51.6 < lat < 51.6, 350 km < z < 450 km, no AE-E
SZA sunrise + 0 < SZA < SZA sunrise + 20



ISR Survey Data

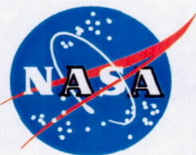
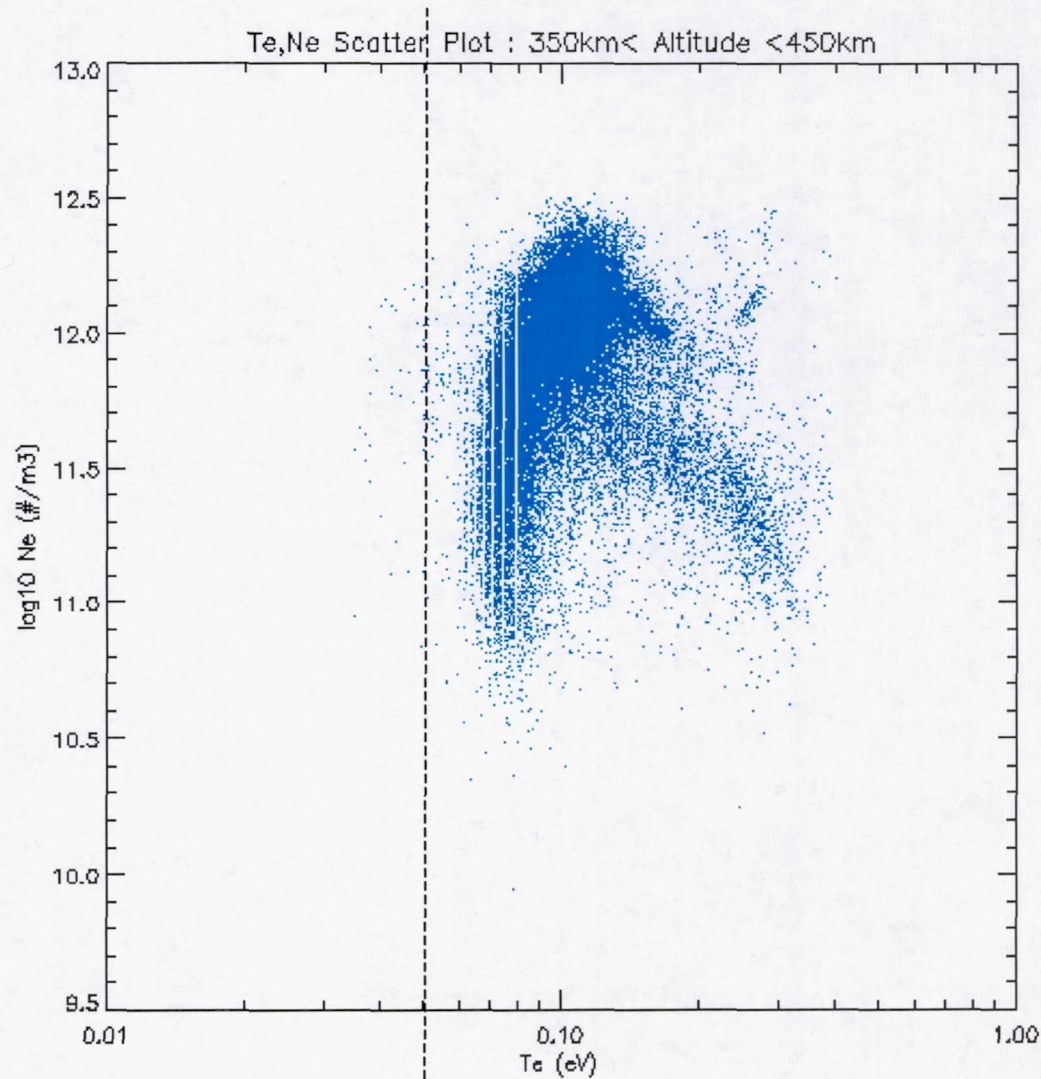
Sondrestrom,
Greenland
1980's



ISR Survey Data

Jicamarca, Peru

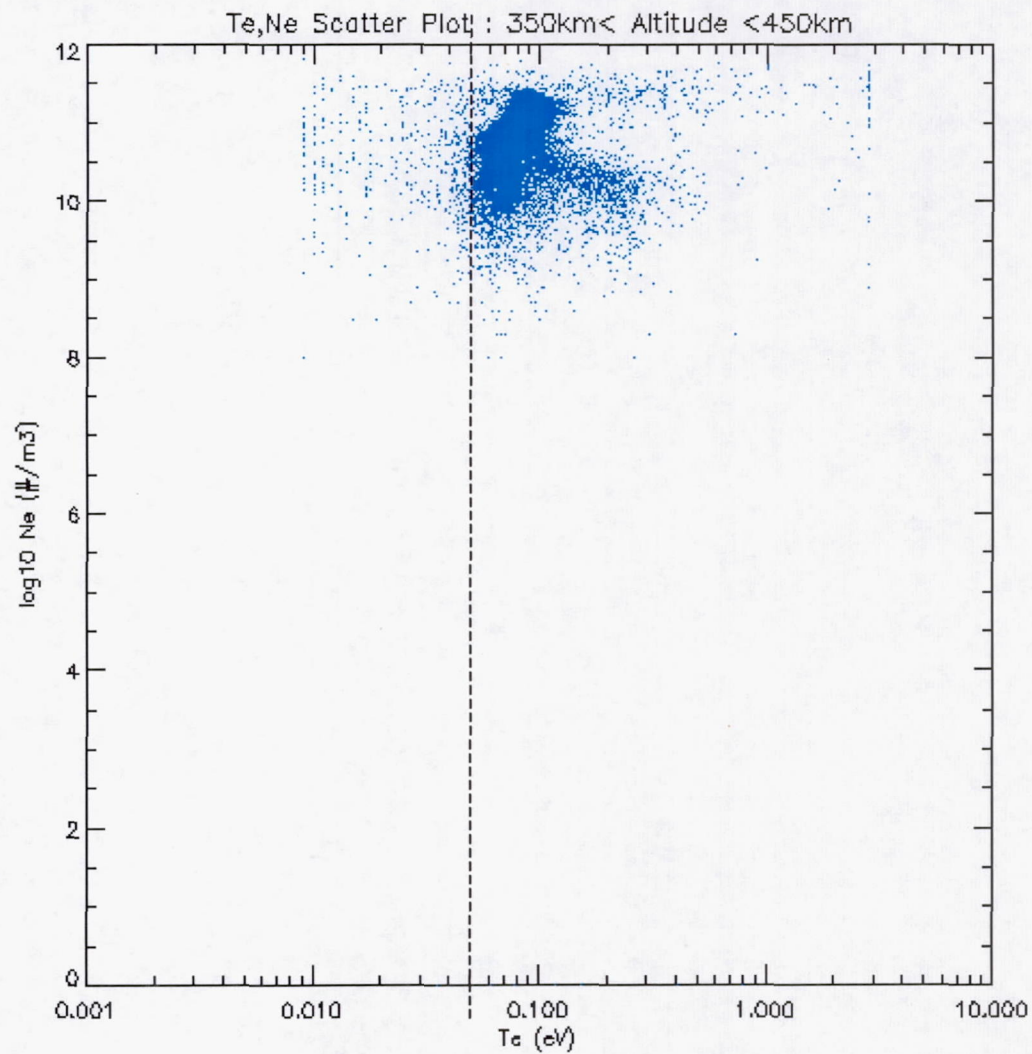
1966 - 1969



ISR Survey Data

Jicamarca, Peru

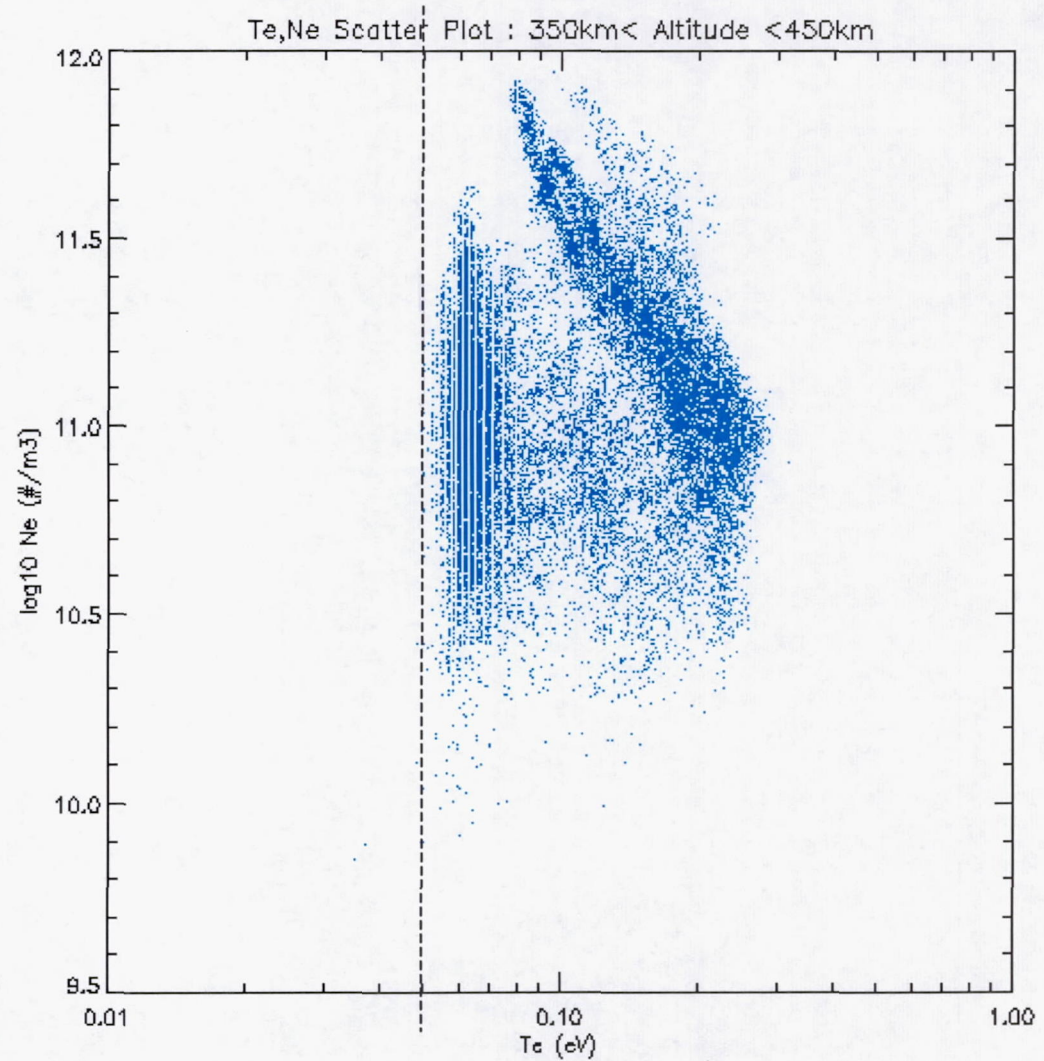
1996 - 1999



ISR Survey Data

Arecibo, Puerto Rico

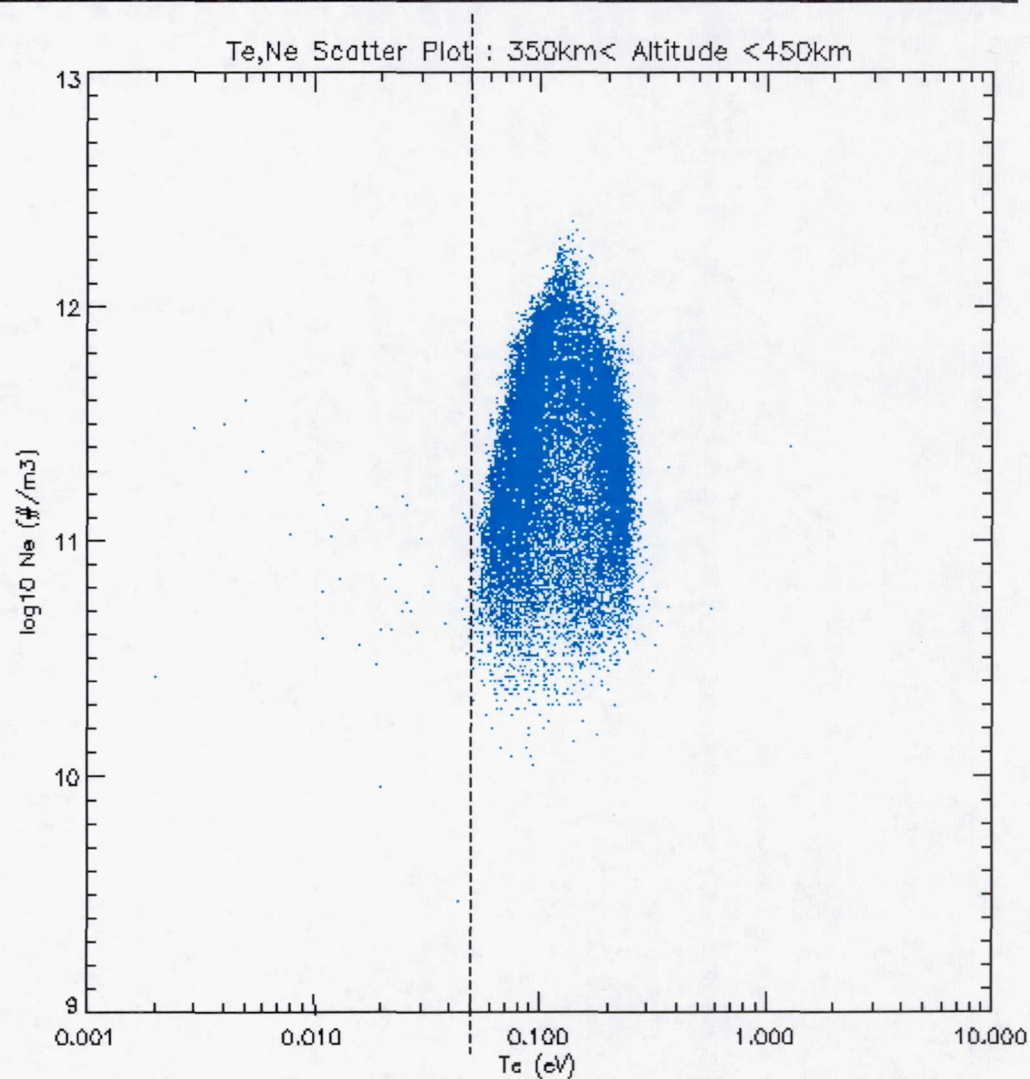
1986 - 1999



ISR Survey Data

St. Santin, France

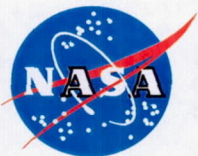
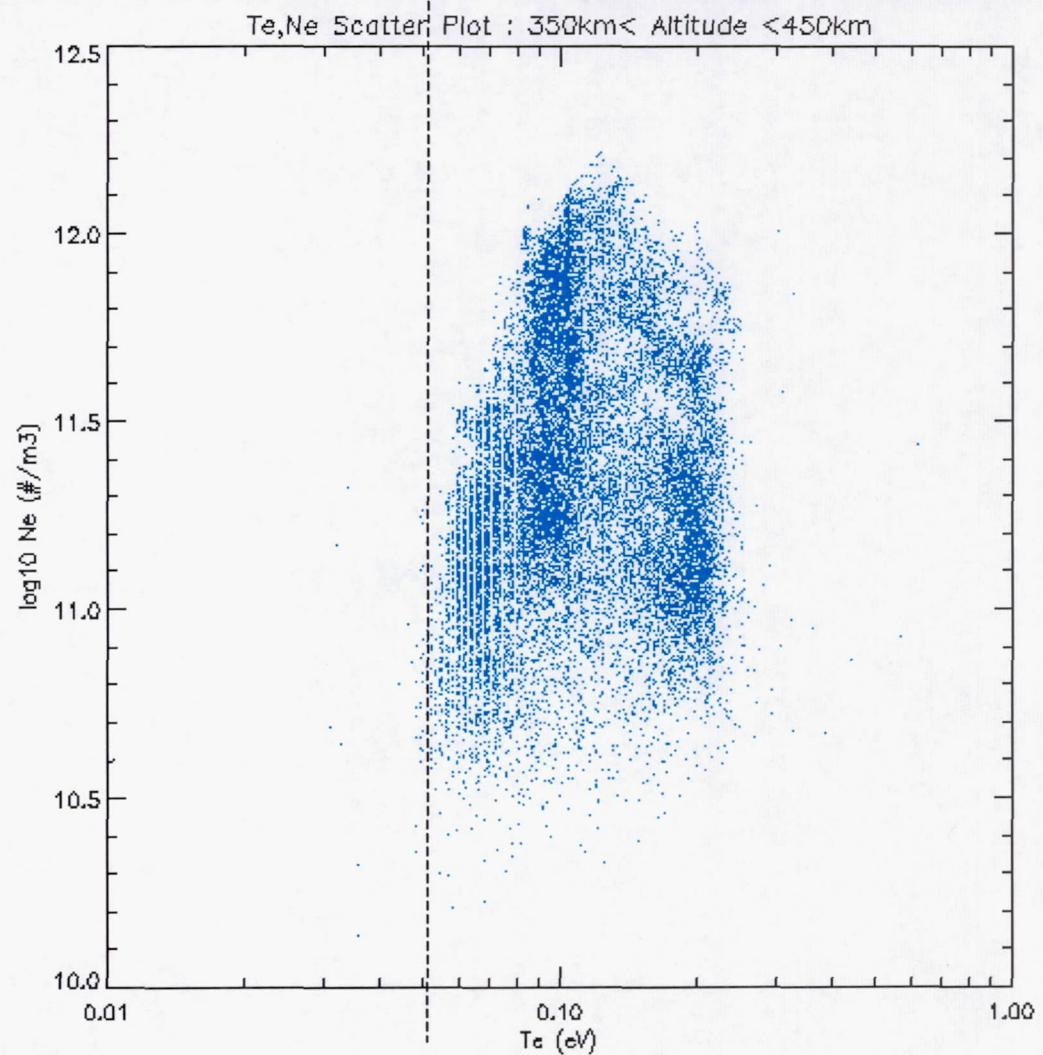
1966 - 1979



ISR Survey Data

St. Santin, France

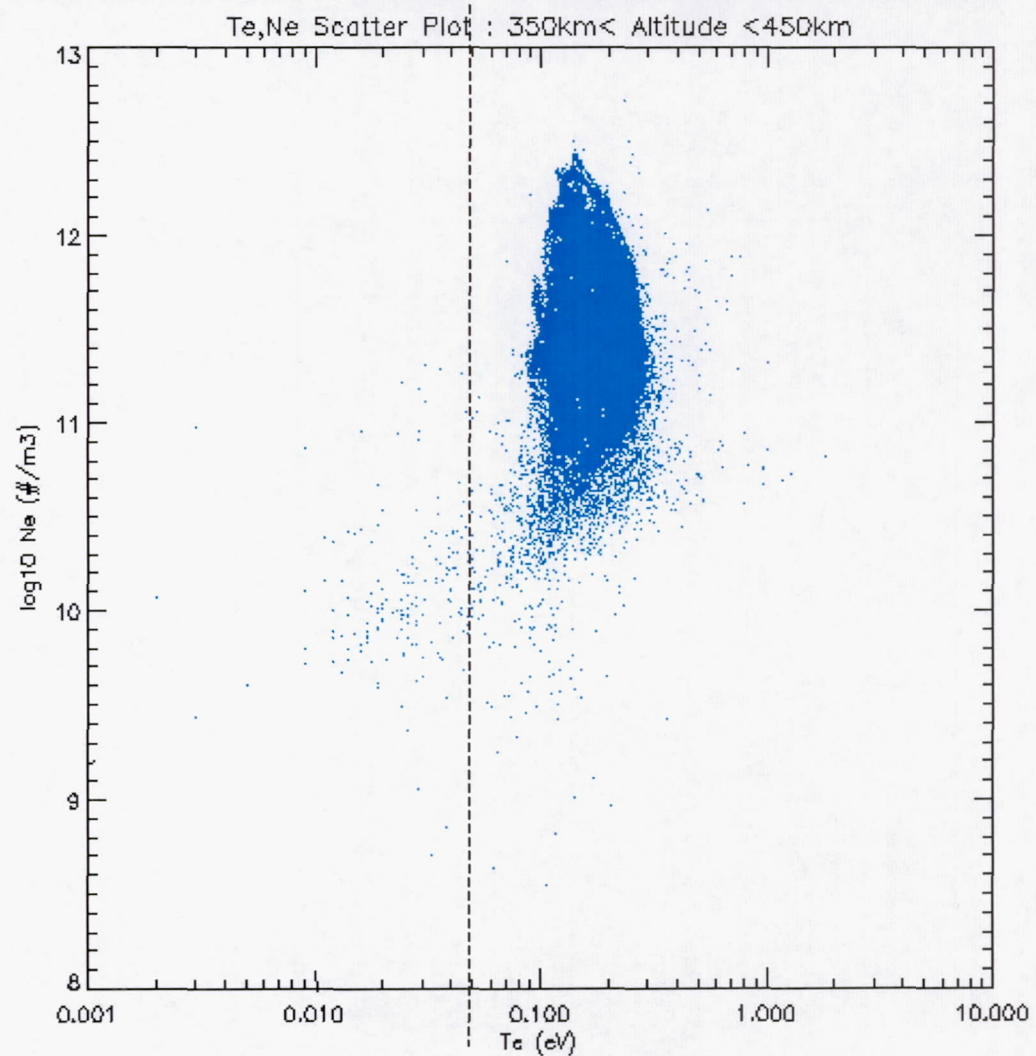
1980 - 1986



ISR Survey Data

Chatanika, Alaska

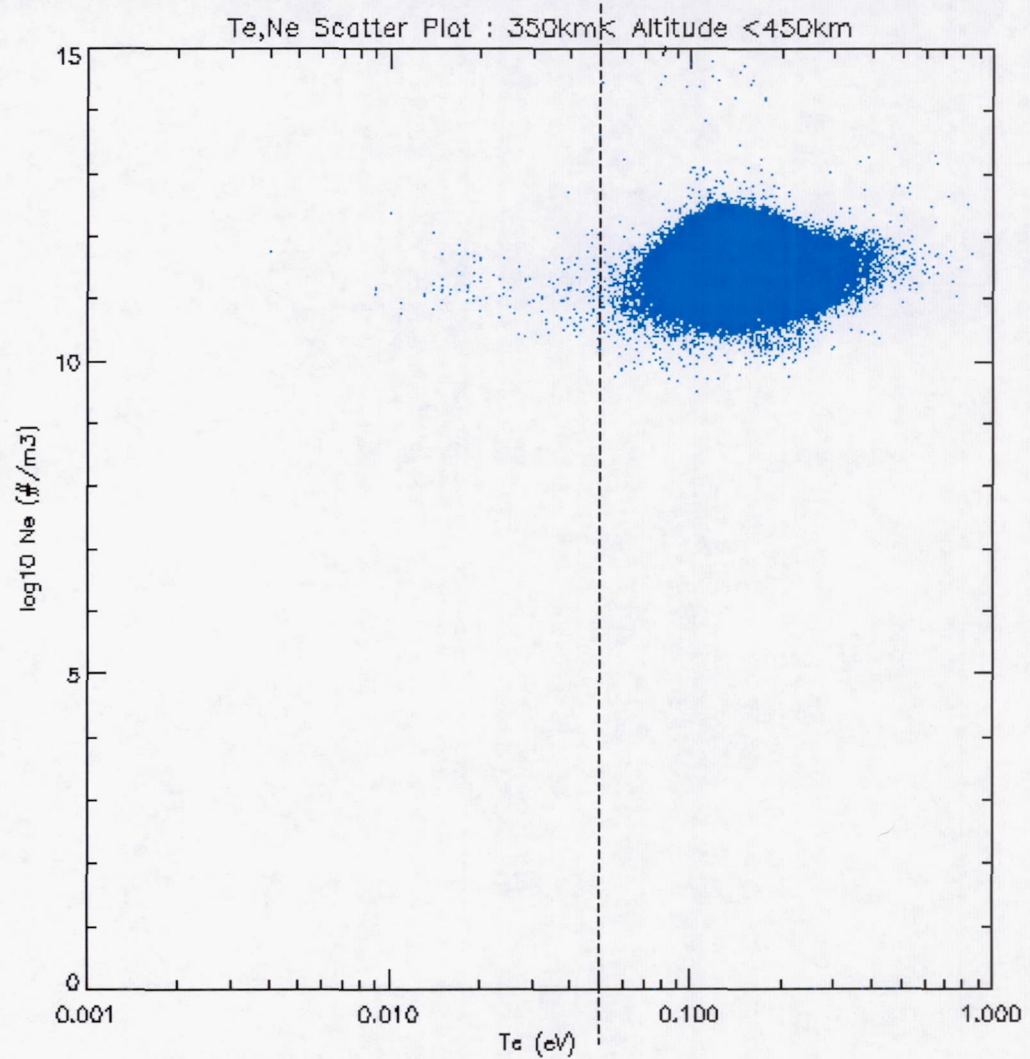
All data



ISR Survey Data

Millstone Hill, MA

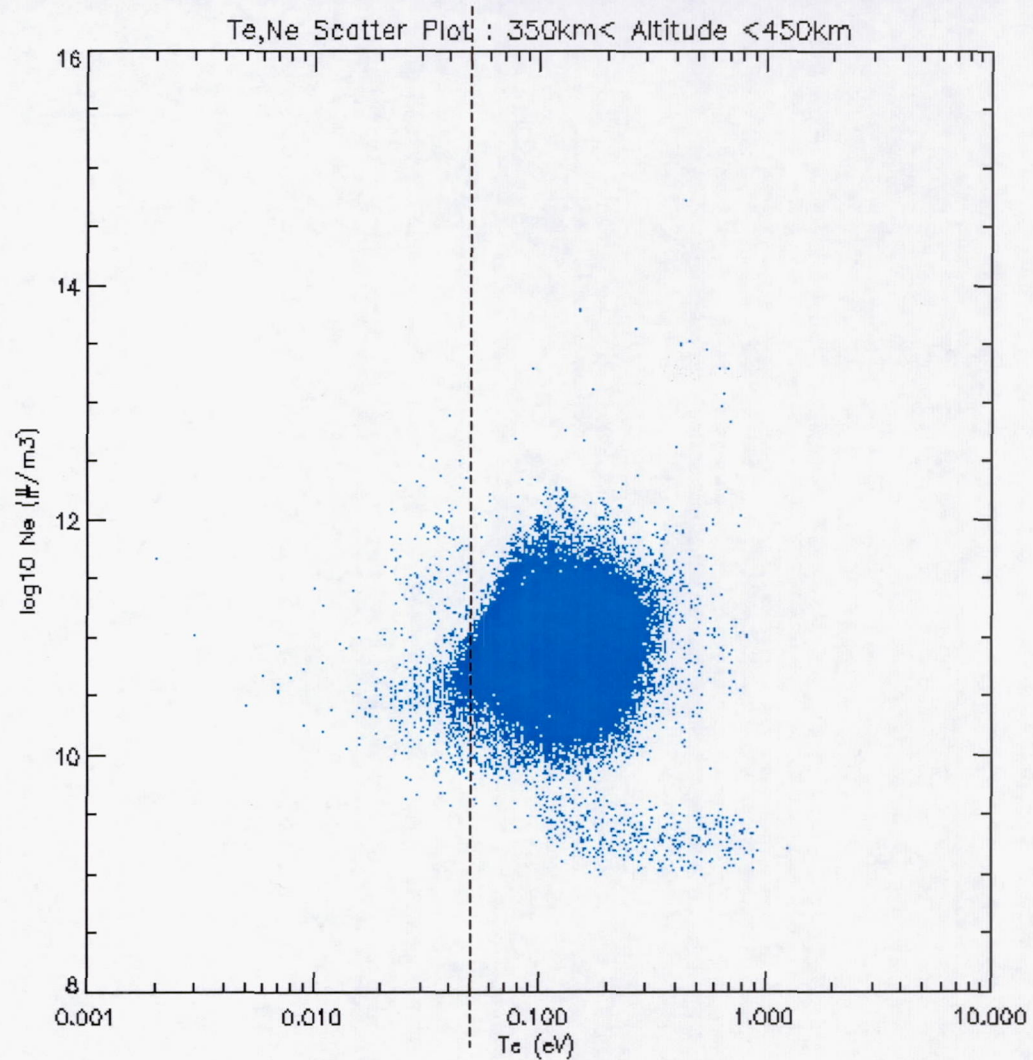
1978- 1984



ISR Survey Data

Millstone Hill, MA

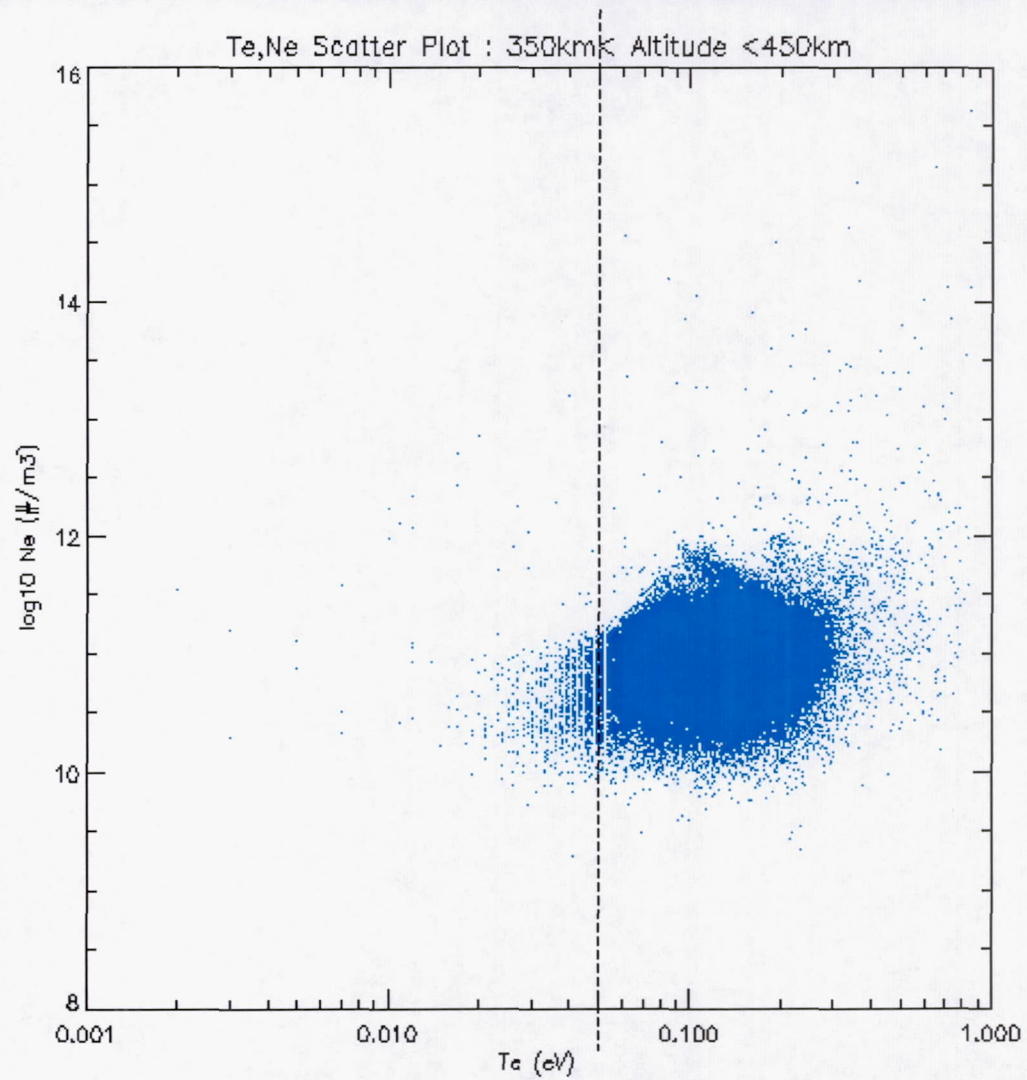
1985



ISR Survey Data

Millstone Hill, MA

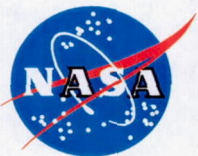
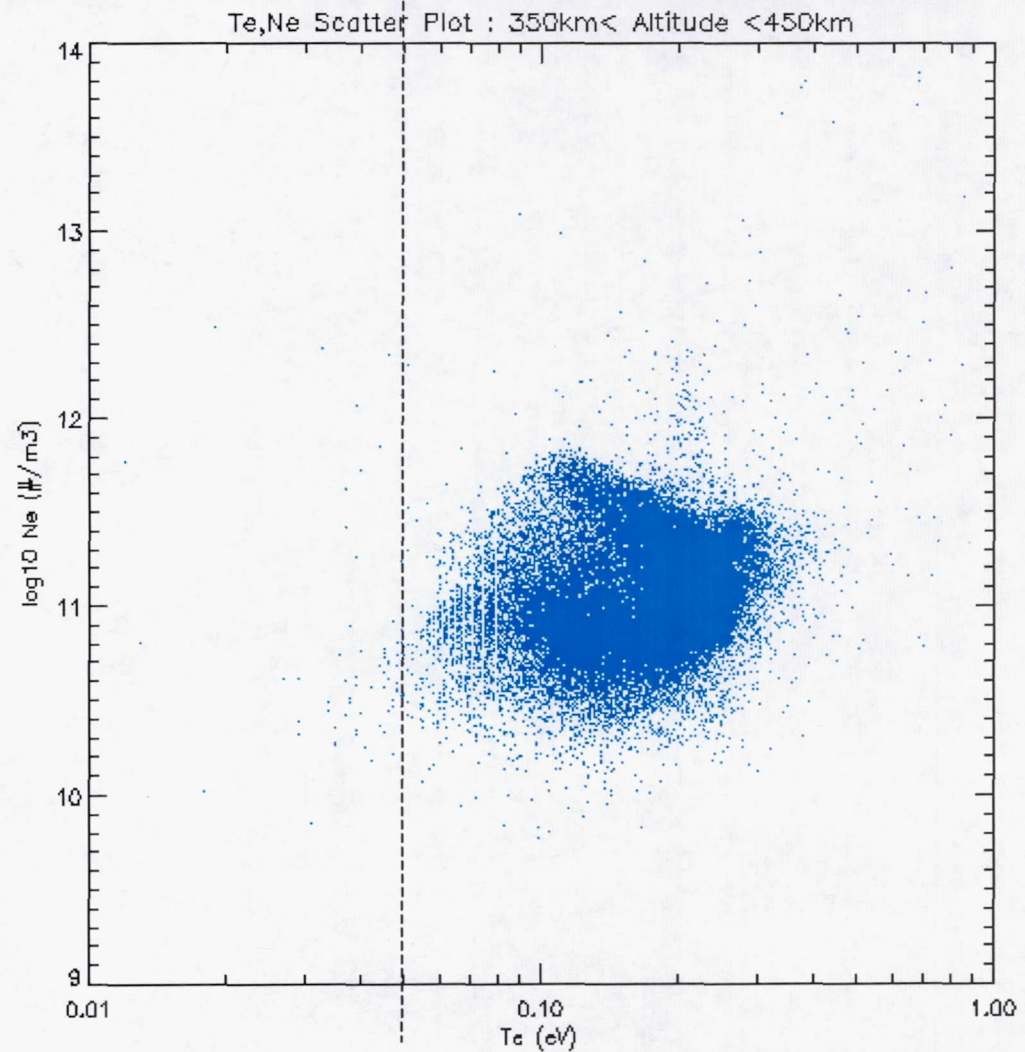
1986



ISR Survey Data

Millstone Hill, MA

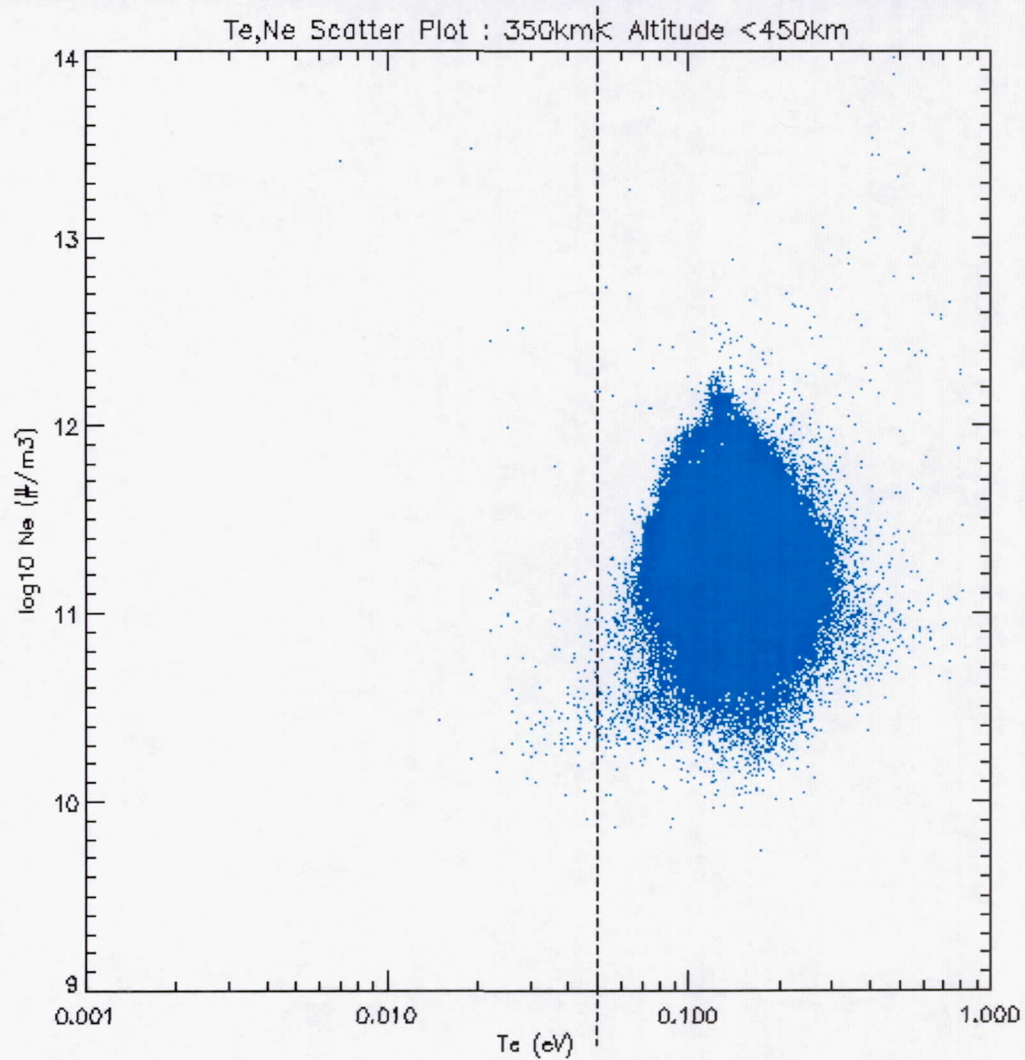
1987



ISR Survey Data

Millstone Hill, MA

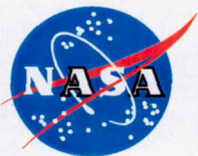
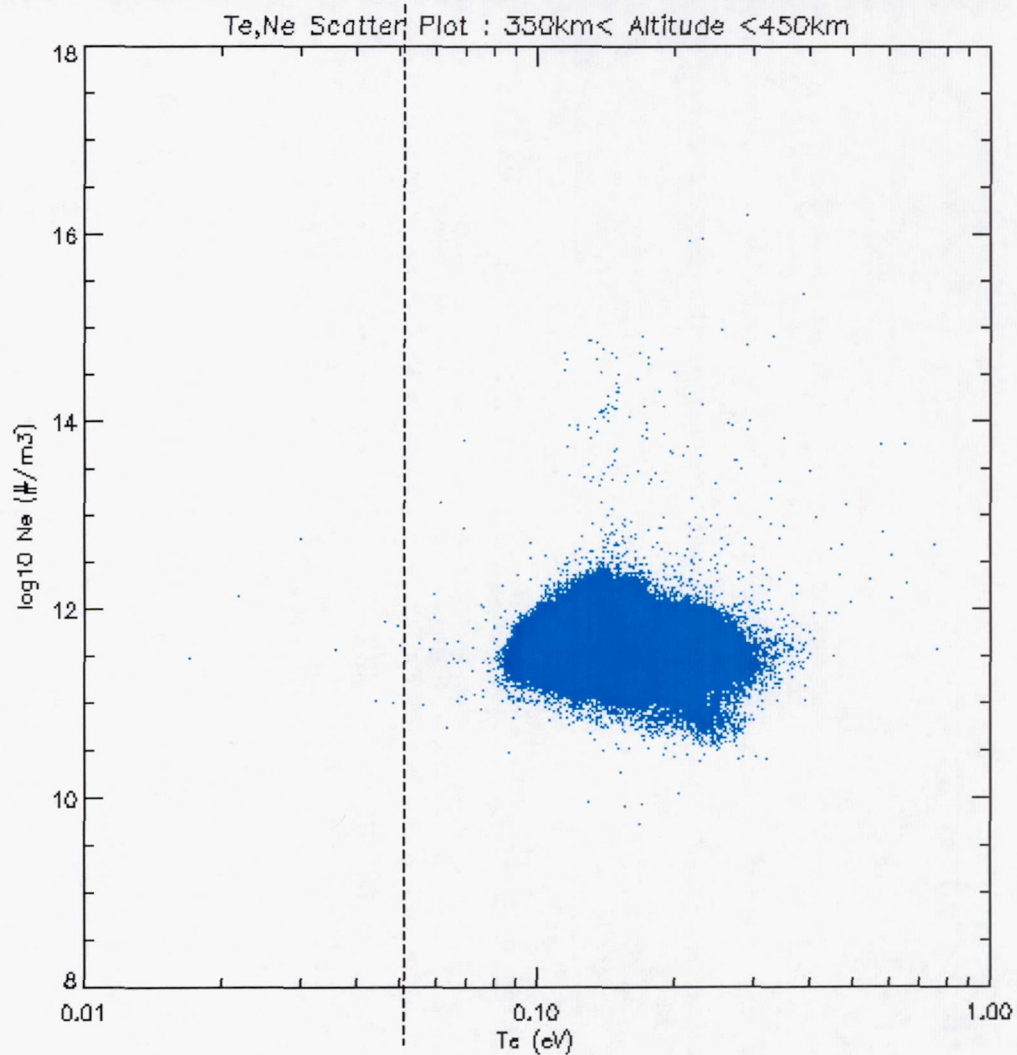
1988



ISR Survey Data

Millstone Hill, MA

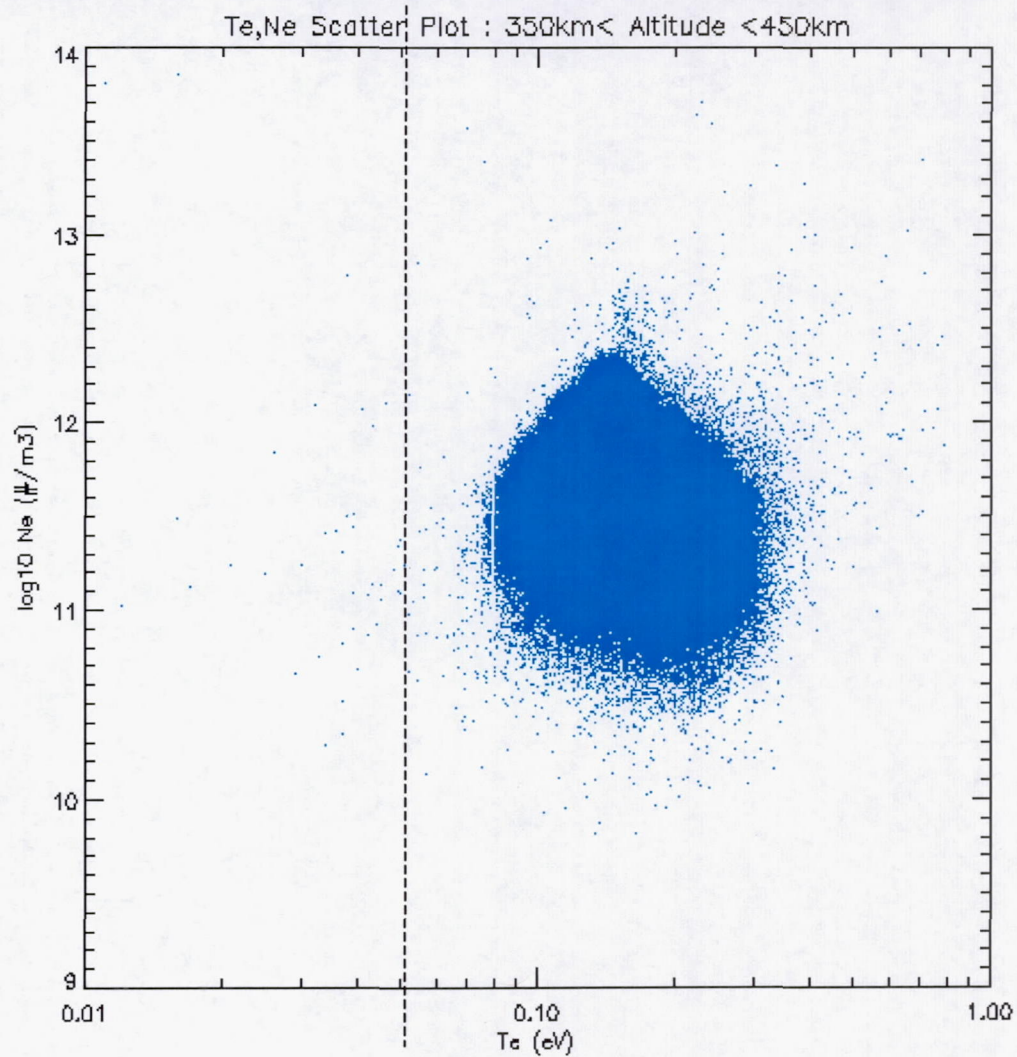
1989



ISR Survey Data

Millstone Hill, MA

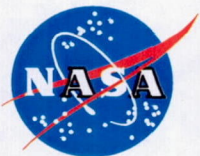
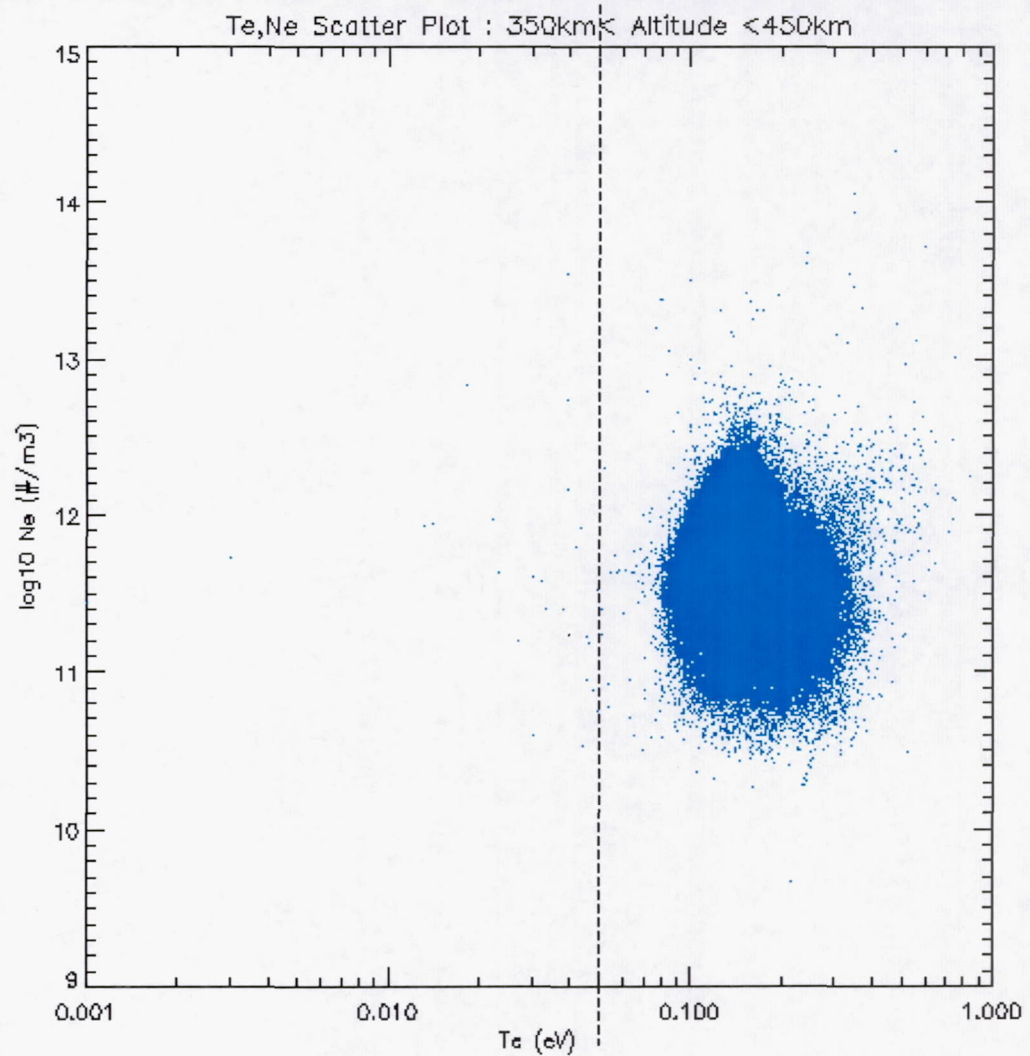
1990



ISR Survey Data

Millstone Hill, MA

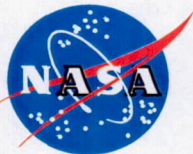
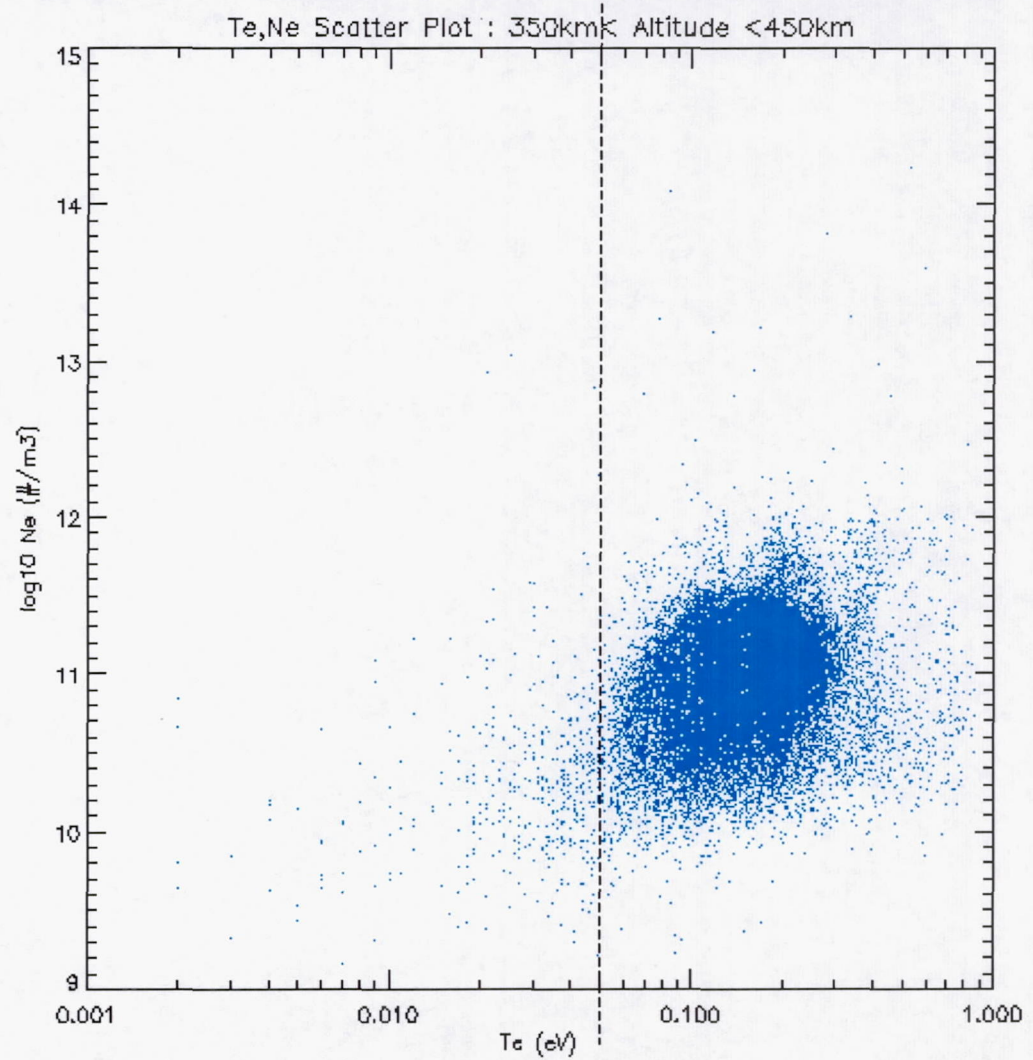
1991-1992



ISR Survey Data

Millstone Hill, MA

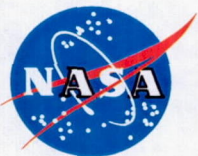
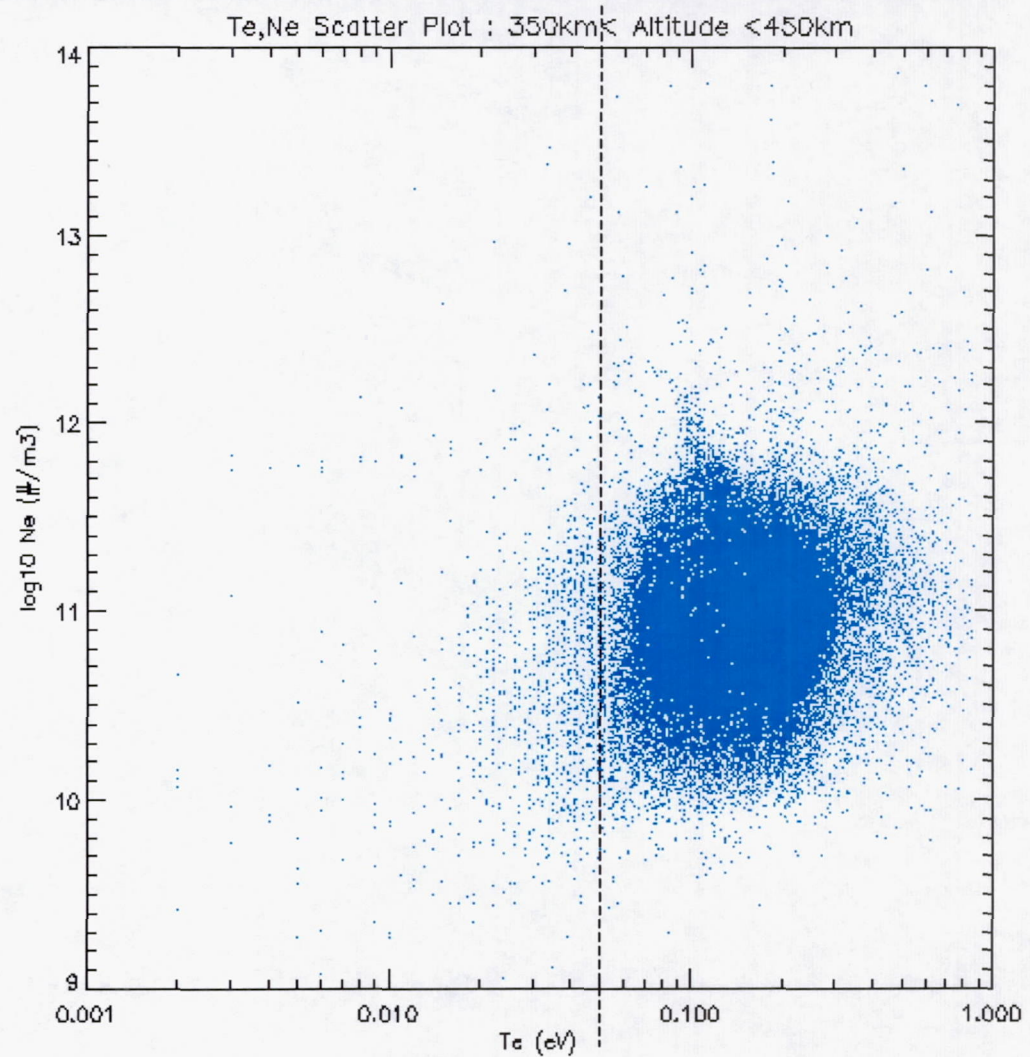
1994



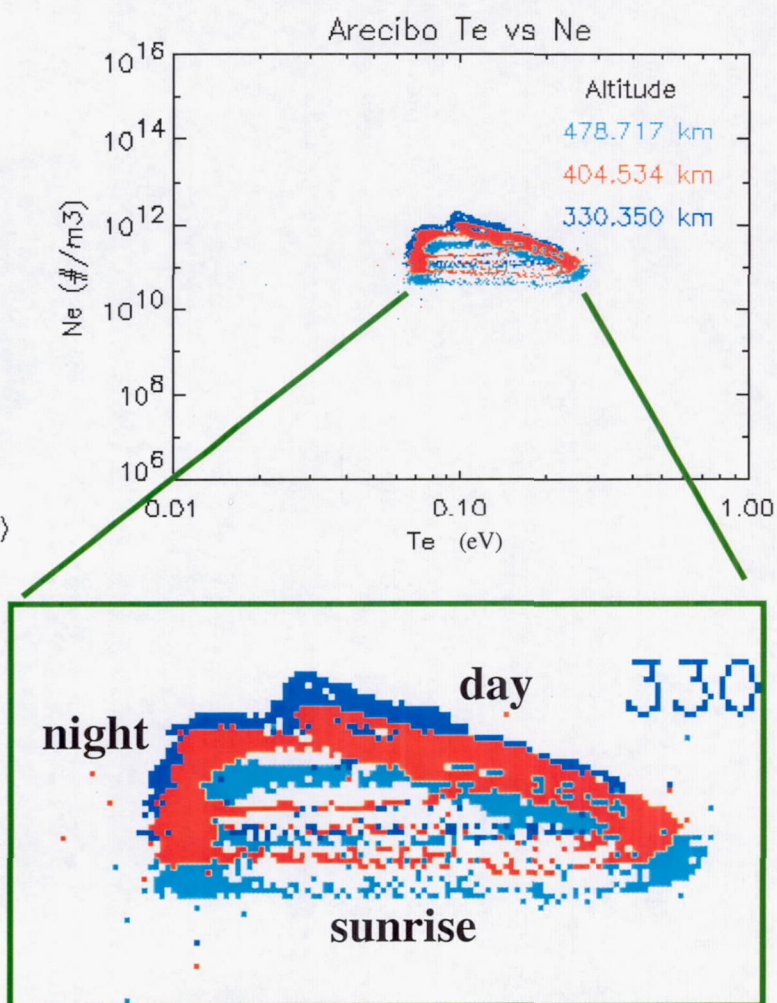
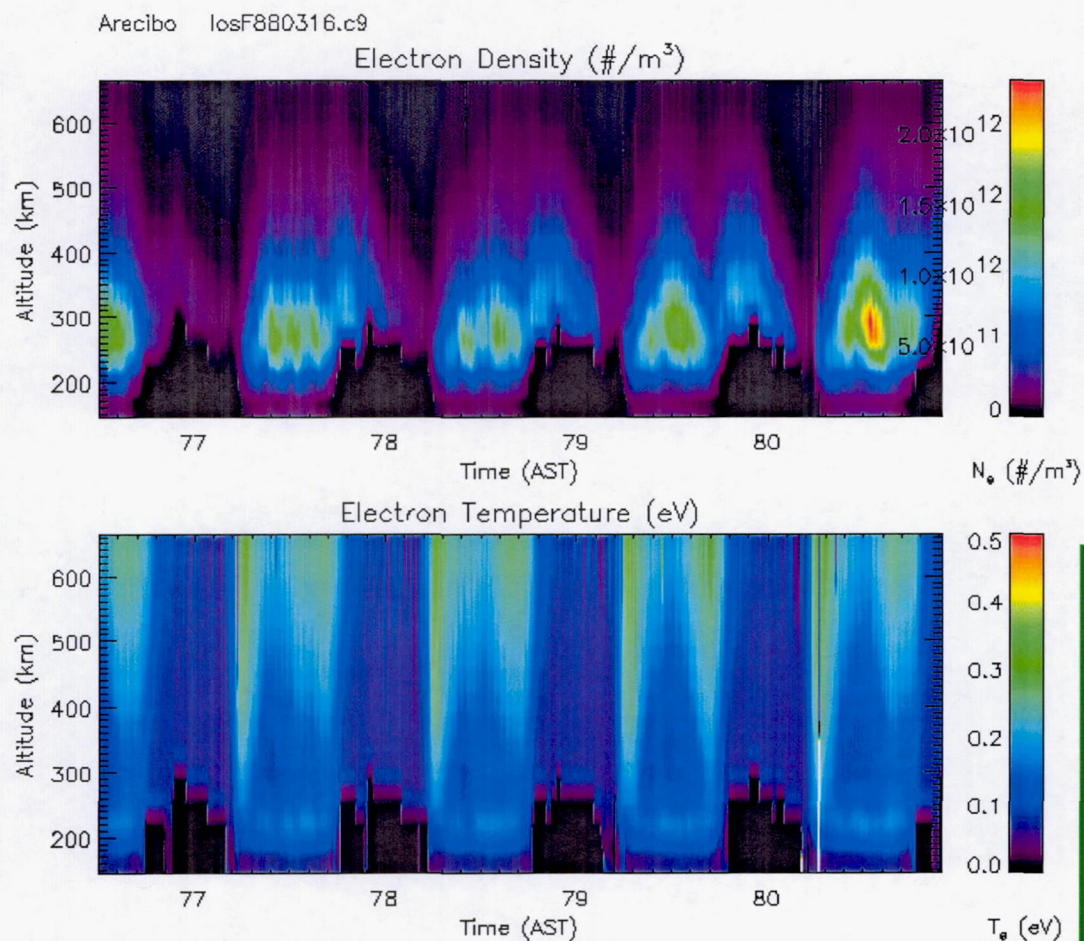
ISR Survey Data

Millstone Hill, MA

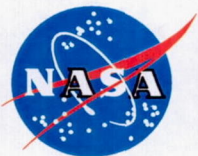
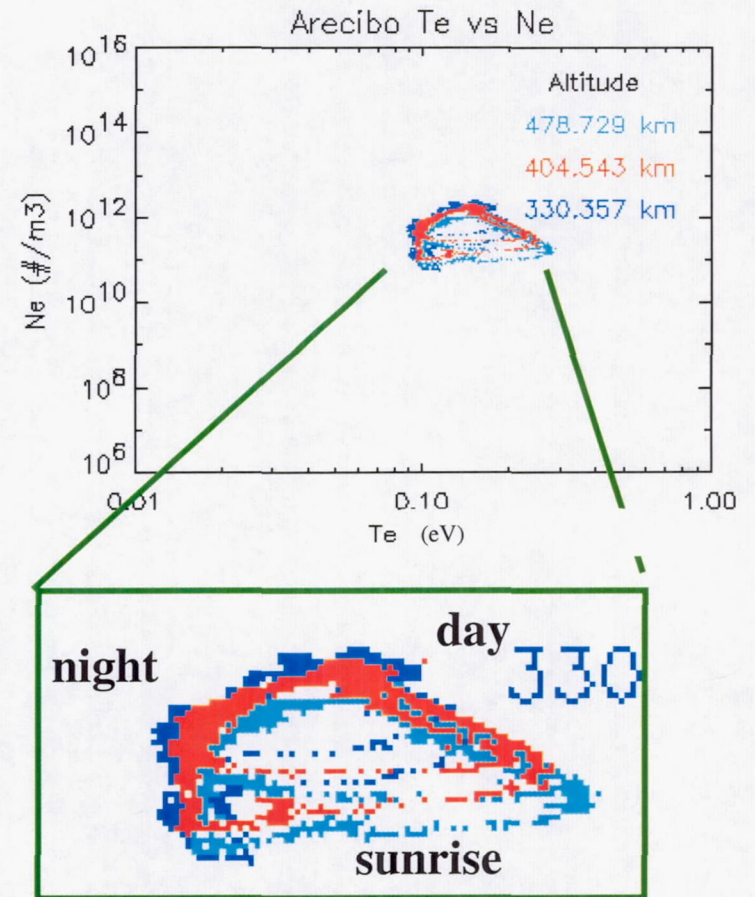
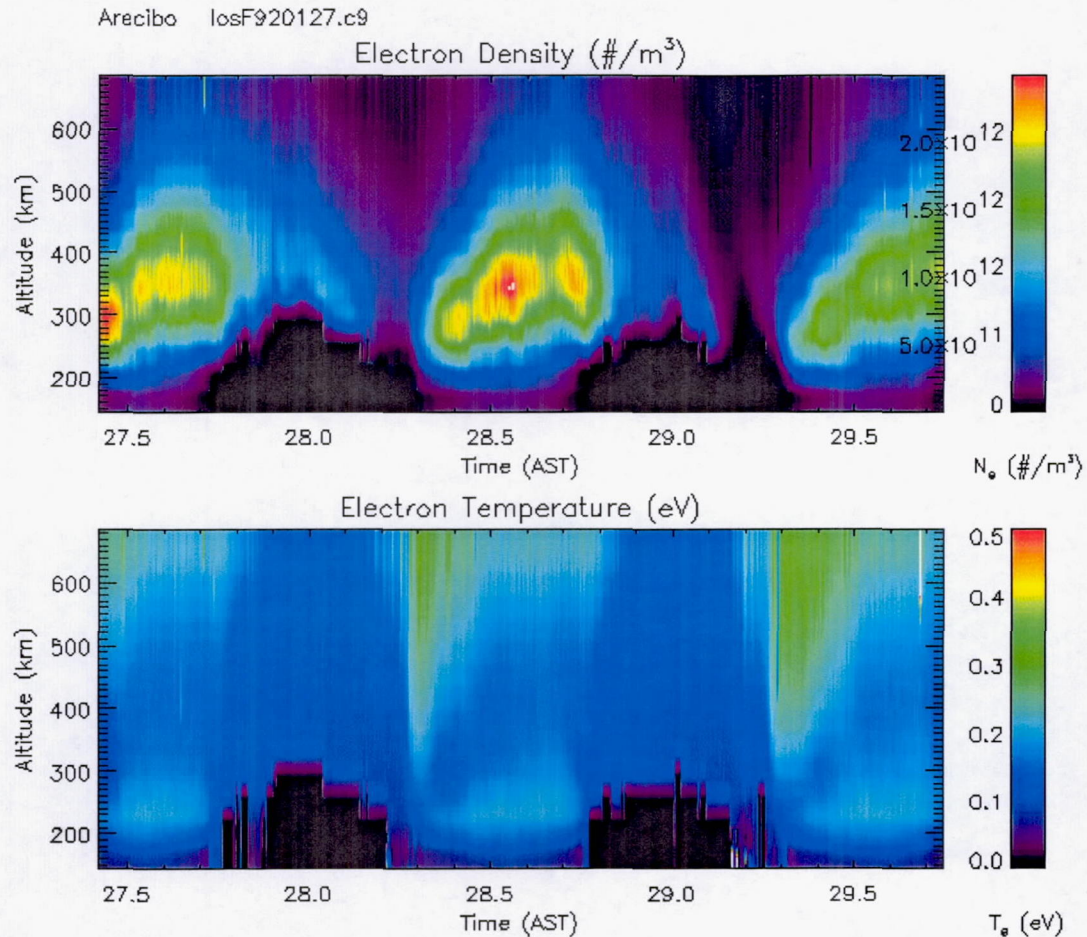
1995



Ne, Te Correlation

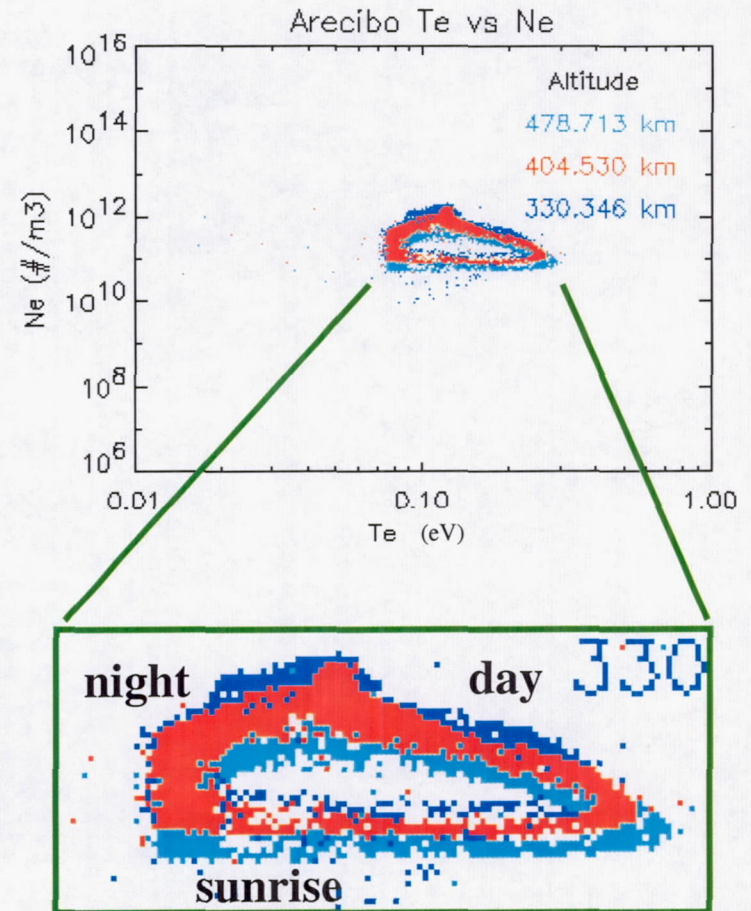
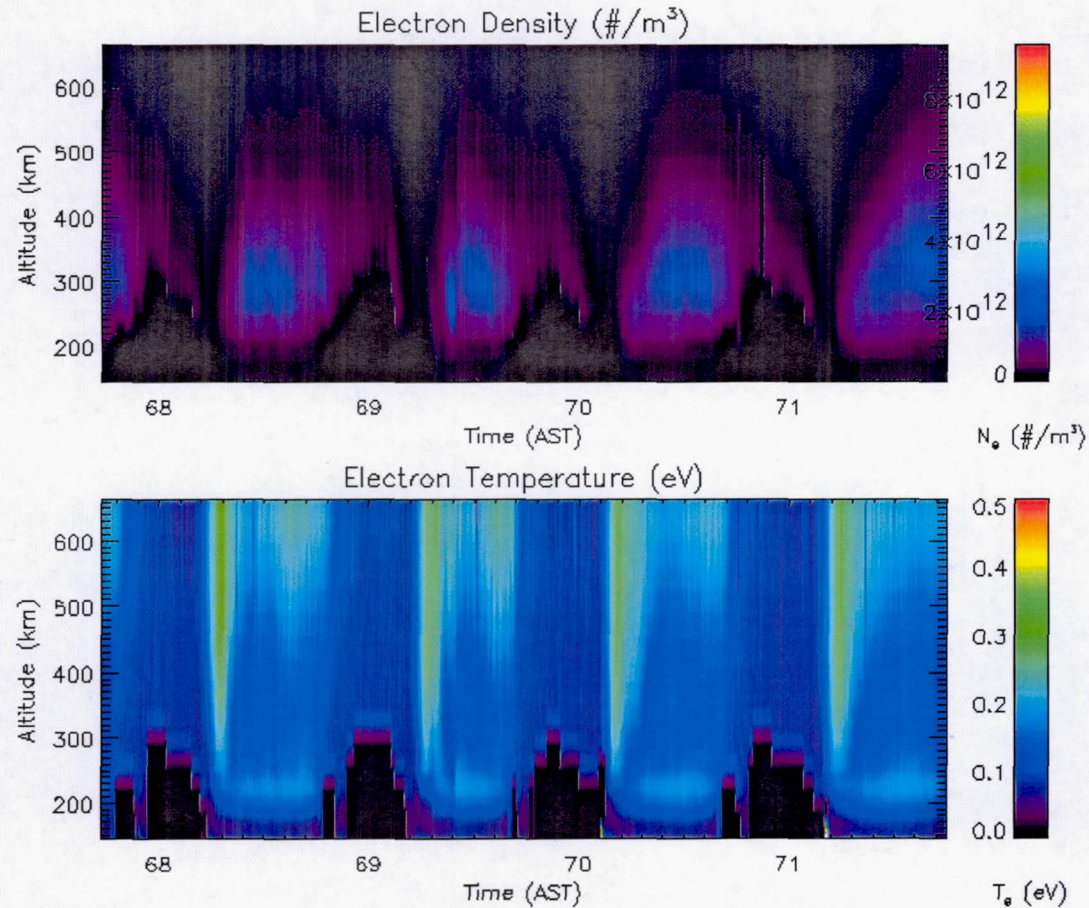


Ne, Te Correlation



Ne, Te Correlation

Arecibo losF990308.c9



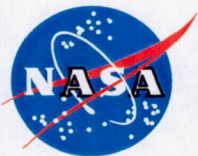
Forward Work

- **Process historical data sets from CEDAR Database for inclusion in variability study**
 - Filter for ISS pre-sunrise conditions
 - Solar cycle pre-sunrise Te, Ne variation
 - Discuss ISR data analysis with PI's
- **Determine if any night ISR Te, Ne measurement will constrain ionosphere model sufficiently well to use for all eclipse exits**
 - Compare available ISR world day data from multiple sites, satellite data
- **Re-analysis of FPP and Millstone Hill ISR data**
 - L. Neergaard completed a more sophisticated model of Millstone radar beam including locations of all radar gates
 - ISS trajectory through Millstone Hill radar beam and identification of intersection of ISS trajectory with radar gates
 - Need to complete comparison of radar Ne, Te data from range gates that intersect ISS orbit with FPP Ne, Te values



Forward Work

- **Analysis of ionosonde Ne values with FPP overpasses**
 - Useful to test process for comparing FPMU density values with ionosonde data
 - NOAA SPIDR database updated with AFRL ionosonde network data on 5-15 minute time scale
 - Issue of $h_m F_2$ retrieval accuracy for automated ionogram scaling used to fill SPIDR database (discussion with NOAA/SEC personnel at 2003 Space Weather Week).
 - Contact R. Vieriek/NOAA/SEC to determine what has been done on historical data analysis
 - AFRL to use ionosonde data in validation of DMSP satellite electron density retrieval from SSULI airglow limb observations
 - B. Reinisch/Lowell Observatory to manually check Air Force network ionograms, scaling
 - DMSP launch with SSULI is TBD.
- **ISS PCU-ISR radar correlation (S. Koontz)**
 - Compare list of ISS PCU operation dates with ISR records to locate coincident observations during ISS overflights of radar sites



Forward Work

- **Write proposals for NSF ISR radar support of FPMU on-orbit check**
 - Sell as science program.....validation of new charging model for high voltage solar arrays?
 - **Millstone Hill**
 - UHF Incoherent Scatter Radar requests submitted ideally 6 weeks before the desired experiment date
 - Coordinated observations between UHF Radar and other instruments submitted ideally 3 months before the desired experiment date.
 - **Arecibo**
 - Proposals due 2 June 2003 for observations from 1 October 2003 – 31 May 2004
 - Need to submit now if FPMU is flown to ISS in March 2004 (this weekend?!)
 - **Jicamarca**
 - Scheduling experiments at Jicamarca is still handled in an informal way. Contact D. Farley at Cornell and/or Ronald Woodman at JRO for details.
 - If you plan to run at night or during Friday-Sunday, you should be prepared to pay overtime charges to the staff members. These charges might add up to \$30-50/hour, depending upon the number of people involved. Staff members are generally very happy to work overtime because payments represent a substantial boost to their income.
 - Cost (NSF supported research): no charge for observing time, other than overtime for staff.
 - Cost(non-NSF supported programs):
 - There is a charge of approximately \$8000 per day of observing for isolated experiments
 - For longer, on-going programs not supported by the NSF, special arrangements must be made with the Observatory.

